Cooling is Hot!

An Energy-Efficient Individual USB Air Conditioner

Dissertation by:

Matthijs Dirk Meulenbelt

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An Energy-Efficient Individual USB Air Conditioner

DISSERTATION

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the degree of doctor at the University of Twente,
on the authority of the rector magnificus,
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Dedicated to:	Eva Meulenbelt & Olivier Meulenbelt.
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Preface

Over 10 years ago I had the idea to use the ceiling of a car to cool down its cabin. And, from recollection of the biology lessons in secondary school, I expected that evaporation of sweat from the human skin would probably be a very effective cooling method. That's why I wanted to use tap water as a coolant. This would make the system very environmentally friendly. Between the ceiling and the roof of a car, there usually is some space, allowing air to flow between them to evaporate water, spread over the upper side of the ceiling, and entrain the water vapour in the airflow to the outside world. I then thought, it would be a good idea to use the speed of the car to induce this airflow from the outside world between the roof and the ceiling, making fans superfluous and making the system also very energy-efficient.

It turned out, this was not a good idea at all: The cooling power would be very little, compared to the air conditioning systems, usually found in cars and, because of the different atmospheric conditions between the outside world and the cabin of the car, condensation may well form on the inside wall of the ceiling, causing rain inside the cabin, just like the instant frosting of the windows of a car when entering in a wet coat.

Still, I could not let go of the idea and conducted some research on how humans lose their heat.

To me, this opened up new possibilities to create an effective device to improve the thermal comfort of a human in an environmentally friendly and energy-efficient way, without the need of a large airflow and with little impact and intrusion on the surroundings of the person using it.

When I met with Professor dr. ir. A.O. (Arthur) Eger, he and I came to speak about designing products with a focus on what people actually want or need instead of what can technically be improved, the latter being the focus of *many* engineers. The cooling device came up for discussion. He suggested, it would be possible to write a dissertation on the design of a product, provided it would cover all (well, most) aspects of the device and this is what came out.

After determining the measurable cooling effect on humans, Arthur and I thought, it should also be determined whether people actually perceive the effect of the cooling device as it is quite subtle in its workings notwithstanding its quite profound results. To me, this approach was completely new as I am- or used to be- one of the *many* engineers. His Faculty of Industrial Design had already embraced this modern outlook on engineering and employed staff, dedicated to this psychological perspective.

Associate Professor dr. T.J.L. (Thomas) van Rompay, behavioural scientist introduced me to, and helped me how to, ascertain- in a scientifically correct way- whether the effect of the cooling device was subconsciously perceived by and indeed beneficial to its users. Thomas and I formulated a blind test,

supposedly concerning the conditions and atmosphere of the interior of a construction trailer, the laboratory space in which the tests were executed.

Later on, Thomas and I formulated yet another sequence of tests, during which the measurable effect of the cooling device was verified.

Because the cooling device differs in two essential aspects from many similar inventions, a patent was applied for. The examination of the European patent application took very long. For this reason, this dissertation was put on hold for a considerable time. Now, a United States patent and a European patent have been granted.

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Borne, The Netherlands, February 2020,

Matthijs Meulenbelt

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Abstract

Generic air conditioning systems use convection as method to cool down their users. This makes for systems, laid out for cooling down the air in entire spaces.

This dissertation reports whether it is feasible to use a different approach to cooling down people:

Change the radiation balance between a person and his environment.

For this purpose, a new cooling device was developed and tested. It focuses on 'radiation absorption' by being- slightly- cooler than its environment, and uses water as a coolant, which may render it very environmentally friendly and efficient, because of the high enthalpy of vaporization of water.

The new cooling device focuses on a single person at a time and leaves the ambient temperature virtually unchanged.

To test the effectiveness of the device and the method it depends on, two series of tests were conducted: One to test whether its users perceive the effect of the device, and one to physically measure whether its users kept cooler at the new cooling device.

The tests showed, that the effect of the new cooling device is *measurable* and indeed *perceived*.

To complete the research on the effectiveness of the device, a single test was performed to establish the longevity of the effect of the new cooling device, also with a positive outcome.

The research shows that the new cooling device gives a cooling effect for a single person in a simple, silent, virtually windless, energy-efficient, environmentally friendly, inconspicuous, comfortable and healthy way.

The novelty of the design was underlined with a granted US- and EU-Patent.

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Introduction

If you have ever entered a car on a hot, sunny day, the A/C set to (too) cold, you'll know how unpleasant this severe, freezing breeze can be. And if you have ever used a portable air conditioner in a room at home, you will know how loud they are, much louder than it seemed in the store. And your papers will blow right off the table.

Most of these commonly known air conditioning systems are designed to reduce the air temperature of the space they are used in, be it a car cabin or any other room. In the course of time they have become quite energy-efficient but still face quite a chore in cooling down all the air in the space to get the desired effect.

In front of you is the description of my challenge to combine the most effective way to cool down a human with the most efficient method of cooling.

It set me the task to develop a result that- apart from being effective- must be simple, silent, virtually windless, energy-efficient, environmentally friendly, inconspicuous, comfortable and healthy.

Chapter 1 covers the heat loss of humans to find the most effective way to cool down.

Chapters 2 to 4 give an overview of existing cooling methods.

Chapters 5 to 11 describe the design and the how and whys of the new cooling device and its technical pre-tests.

Chapter 12 relates to the tests, which were performed to see, whether the users of the new cooling device really benefit from the cooling device and *perceive* its cooling effect, as its effect is quite subtle yet physiologically very effective.

Chapter 13 verifies the measurable effect of the new cooling device.

Chapter 14 covers the granted patents and

Chapter 16 describes an extended test of the new cooling device.

In this dissertation, spelling will be GB-English: A dm³ will be referred to as litre, 100 cm as metre and the gas-like form of water as vapour, and numbers are displayed in the European style wherein a comma is used in front of the decimals rather than the imperial style wherein a decimal point is used in front of the decimals. The absolute zero is maintained at -273,15°C, disregarding the redefinition of May 20, 2019.

(empty)

1: **How humans lose their heat**

Books on Physiology for (undergraduate) medical students, without exception, devote a chapter to the energy household of the human body, its energy consumption, energy balance and heat loss. The last item, heat loss, will show what may be the efficient way to cool down a human.

The main mechanisms of a human to lose his heat are (University of Notre Dame, 2003; Paulev & Zubieta-Calleja, 2004):

- **Cooling by conduction:**

When two solid materials of different temperature are in contact with each other, heat will exchange between them.

For a human, this is heat loss through parts of the body that are covered by anything: Clothes will exchange heat with the human body as will the seat of a chair. More exaggerated:

A human will cool down when in direct contact with ice.

- **Cooling by convection:**

This is the heat transfer between a moving medium (gaseous or liquid) and another medium (gaseous, solid, or liquid).

A human will exchange heat with the air in his vicinity. Hotter air is lighter than cool air and will therefore rise, thus causing air flowing along a human.

A human will cool down when in contact with flowing colder air.

- **Cooling by radiation:**

This is the heat transfer via electromagnetic waves or photons.

On colder days, cafe terraces may have these radiant heaters that have reflectors and make humans perceive heat instantaneously.

The reverse also applies:

A human will cool down when exposed to a cold wall or window.

- **Cooling by evaporation:**

When evaporation occurs, heat is extracted- from the remaining liquid or the surface it was on before evaporation- by the vaporizing liquid.

Apart from some heat, trapped in the water vapour in exhaled air, humans have a system of sweat glands that secrete small amounts of a watery solution that extracts heat from the skin when evaporated.

A human will cool down when sweat evaporates from his skin.

Laws of nature dictate the first 3 methods. The last one is controlled by the human internal temperature control system (University of Notre Dame, 2003).

A human needs to lose 70 - 100W of heat at rest to close to 1.000W under extreme physical strain and that 30 - 70% of this heat will be lost by radiation, depending on the amount of exposed skin area (Silverthorn, 2013).

On hot summer days, humans will wear less covering and less insulating clothes than on cold days in the winter. People will dress differently and hence expose different amounts of skin, so a general pattern of heat loss can only be established by approximation, although it is very well possible to establish the heat loss per individual case.

1.0 Human heat loss mechanisms

To get a grip on what is the most important mechanism of heat loss, the break down of a naked exemplary human of 70 kg can be approximated, based on some assumptions (Paulev & Zubieta-Calleja, 2004):

- The average skin area A_{BODY} of a human is $1,8 \text{ m}^2$;
- The average skin temperature of a human T_{SKIN} is $33^\circ\text{C} / 306,15\text{K}$;
- A person will evaporate about 800 g of water per day by sweating and breathing, averaging $V_{\text{SWEAT}}, 800 \text{ g} / (24 \text{ h} \times 60 \text{ min}) = 0,56 \text{ g} / \text{min}$;
- The air temperature T_{AIR} and the temperature T_{OBJECT} of the walls of the room is assumed to be $30^\circ\text{C} / 303,15\text{K}$, the maximum thermo-neutral or comfortable temperature at which humans will not sweat actively.

The heat, stored in a body,

$$DH_{\text{STORED}} = DH_{\text{METABOLIC}} - (DH_{\text{RADIATION}} + DH_{\text{CONVECTION}} + DH_{\text{EVAPORATION}})$$

in which:

- $DH_{\text{METABOLIC}}$ = Heat, generated by metabolism;
- $DH_{\text{RADIATION}}$ = Heat loss (or gain) by radiation;
- $DH_{\text{CONVECTION}}$ = Heat loss by convection and a negligible amount of conduction;
- $DH_{\text{EVAPORATION}}$ = Heat loss via sweating and exhalation.

If DH_{STORED} is nought, there is no heat uptake or heat loss. The parts right of the minus can be calculated from the assumptions above:

1.1 Heat loss via radiation

Radiant heat loss (or heat gain) $DH_{\text{RADIATION}}$ for a naked person with a skin temperature T_{SKIN} and a skin area A_{BODY} in an environment with T_{OBJECT} is calculated from the simplified equation:

$$DH_{\text{RADIATION}} = 0,5 \times A_{\text{BODY}} \times (T_{\text{SKIN}} - T_{\text{OBJECT}})$$

in which:

- 0,5 = An equation-specific constant in $\text{kJ min}^{-1} \text{m}^{-2} \text{K}^{-1}$,

incorporating *all* other factors in the equation (e.g. T^4 ; see Paragraph 1.6), which amounts to:

$$\begin{aligned} DH_{\text{RADIATION}} &= 0,5 \times 1,8 \times (306,15 - 303,15) = 0,5 \times 1,8 \times -3 \\ &= -2,7 \text{ kJ} / \text{min} \text{ or } -2700 / 60 \text{ J} / \text{s} \\ &= \mathbf{-45 \text{ Watt}}, 45 \text{ Watt of heat loss via radiation.} \end{aligned}$$

1.2: Heat loss via convection

The heat loss by convection of an upright naked person resting in quiet air without physical movement is given by the- again- simplified equation:

$$DH_{\text{CONVECTION}} = 0,5 \times (T_{\text{AIR}} - T_{\text{SKIN}}) \text{ in kJ / min,}$$

in which 0,5- again- incorporates *all* other factors, amounting to:

$$\begin{aligned} DH_{\text{CONVECTION}} &= 0,5 \times (303,15 - 306,15) = 0,5 \times -3 \\ &= -1,5 \text{ kJ / min} = -1500 / 60 \text{ J / s} \\ &= \mathbf{-25 \text{ Watt}}, 25 \text{ Watt of heat loss by convection.} \end{aligned}$$

1.3: Heat loss via evaporation

Evaporation of water ideally extracts 2.260 J / g from the skin (BINAS, 1998).

The loss of heat via evaporation of sweat follows:

$$\begin{aligned} DH_{\text{EVAPORATION}} &= -2.260 \text{ (J / g)} \times V_{\text{SWEAT}} \text{ (g / min)} \\ &= -2.260 \times 0,56 = 1.255 \text{ J / min} = 1.255 / 60 \text{ J / s} \\ &= \mathbf{-21 \text{ Watt}}, \text{ a heat loss of 21 Watt via evaporation.} \end{aligned}$$

In summary:

Table 1

Heat loss breakdown for a naked human under given circumstances

heat loss mechanism	energy (Watt)	percentage
Conduction	negligible	~ 0%
Convection	25	~ 27%
Radiation	45	~ 50%
Evaporation	21 +	~ 23% +
Total	91	100%

This example shows, that it seems not very efficient to focus on convection- what is what generic air conditioners do- when trying to cool down a human. It implies that the focus should be concentrated on the balance of radiation rather than cooling down the air for more cooling via convection.

1.4 What exactly is thermal radiation?

Encyclopedia Britannica defines thermal radiation (n.d.), as

Process by which energy, in the form of electromagnetic radiation, is emitted by a heated surface in all directions and travels directly to its point of absorption at the speed of light; thermal radiation does not require an intervening medium to carry it.

This means, that all heated objects- that is: *With a temperature above the absolute zero-* that ‘can see’ each other are in constant exchange of thermal radiation. A human radiates heat to- for example- the walls of the room he is standing in and in return, the walls will radiate heat to the human. The human from table 1 radiates 45 Watt more that he receives.

1.5 The human’s minimum heat production and its break down

The so-called basal metabolic rate (BMR)- which is the measurement of human energy consumption (and consequently heat generation) at rest- is the lowest possible $DH_{\text{METABOLIC}}$ from Paragraph 1.0 and breaks down as follows for the 70 kg-human:

Table 2

Basal Metabolic Rate (BMR) breakdown for the 70 kg-human at rest

organ	energy consumption (kcal / day)	% of BMR
Heart	117	~ 7%
Lung	35	~ 2%
Kidney	180	~ 10%
Liver & Spleen	470	~ 27%
Brain	325	~ 19%
Skeletal Muscle	310	~ 18%
Remainder (The rest of the energy used)	293 +	~ 17% +
Total	1.730	100%

After: Physics in Medicine, Part I, Chapter 2.2 (University of Notre Dame, 2003).

These values apply to a human at rest, without making any conscious effort to move. As the human body retains a very constant core temperature and, because of the law of conservation of energy, all energy from Table 2 eventually has to be converted into heat which must be dissipated. Calculating regressively to Watts again, a human at rest will need to lose 1.730 kcal / day which equals 7.238.320 J / day or 7.238.320 J / 86.400 s = 83,8 J / s, or circa 84 Watt. The human from Table 1 dissipated 91 Watt, leaving 7 Watt, apparently needed for being upright and aware.

The table shows, most heat will accrue from the liver and spleen (27%), followed by the brain at 19% whereas the brain only represents 2,5% of the body weight (Silverthorn, 2013). The brain actually has to lose more heat than the unspecified part of the break down (the *Remainder* in Table 2) that also includes the skin.

1.6: The human as a perfect blackbody.

To get an understanding of the absolute amounts of radiation involved, the human head could be considered as a spherical perfect blackbody of Ø 0,2m and 33°C / 306,15K.

Encyclopedia Brittanica defines blackbody (n.d.), as

Blackbody, in physics, a surface that absorbs all radiant energy falling on it. The term arises because incident visible light will be absorbed rather than reflected, and therefore the surface will appear black. The concept of such a perfect absorber of energy is extremely useful in the study of radiation phenomena.

This works both ways: According to the Stefan-Boltzmann law, the total, absolute, amount of energy, radiated from a blackbody with a temperature T, *not* taking into account the radiation received from the environment, will be:

$$E = \sigma T^4$$

In which:

- E = Energy in Watt / m²
- σ = Stefan-Boltzmann constant: $5,670 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$
- T = Temperature in Kelvin

This equation shows, that T⁴ determines the order size of radiation (and not T¹ as in conjunction with the *equation-specific* constant of 0,5 that was used in Paragraph 1.1).

E is the *absolute* radiation: What a blackbody would radiate outbound in the shadow in cosmic space, where the ambient temperature is 0 Kelvin, the *absolute zero*, and there is no inbound radiation.

The absolute outbound radiation per square metre under the given circumstances is:

$$\begin{aligned} E_{\text{/ SQUARE METRE}} &= 5,670 \times 10^{-8} \times 306,15^4 = 5,670 \times 10^{-8} \times 8,785 \times 10^9 \\ &= \mathbf{498 \text{ W / m}^2} \end{aligned}$$

The surface area of a sphere of Ø 0,2 m is

$$\begin{aligned} A_{\text{SPHERE}} &= 4 \pi r^2 = 4 \pi 0,1^2 \\ &= \mathbf{0,1257 \text{ m}^2} \end{aligned}$$

Therefore, the heat, radiated from the (abstract) perfect blackbody head is:

$$\begin{aligned} E_{\text{HEAD}} &= E_{\text{/ SQUARE METRE}} \times A_{\text{SPHERE}} = 498 \text{ W / m}^2 \times 0,1257 \text{ m}^2 \\ &= \mathbf{62,6 \text{ Watt}} \end{aligned}$$

When a human is seated at rest, dressed for high summer and directly exposing 25% of his skin and not taking into account the radiation from his clothes, again according to the Stefan Boltzmann law, the entire body radiates:

$$\begin{aligned} E_{\text{BODY@25\%}} &= A_{\text{BODY}} \times E_{\text{/ SQUARE METRE}} \times 0,25 \\ &= 1,8 \text{ m}^2 \times 498 \text{ W / m}^2 \times 0,25 \\ &= \mathbf{224,1 \text{ Watt}} \text{ in outbound radiation.} \end{aligned}$$

Similarly, 50% of exposed skin will release

$$\begin{aligned} E_{\text{BODY@50\%}} &= 2 \times E_{\text{BODY@25\%}} = 2 \times 224,1 \text{ Watt} \\ &= \mathbf{448,2 \text{ Watt}} \text{ in outbound radiation.} \end{aligned}$$

This means, that the head may be responsible for:

$$\begin{aligned} (E_{\text{BODY@25\%}} \div E_{\text{HEAD}} &= 448,2 \text{ Watt} \div 62,6 \text{ Watt}) \\ &\approx \mathbf{1/7} \end{aligned}$$

to

$$\begin{aligned} (E_{\text{BODY@50\%}} \div E_{\text{HEAD}} &= 224,1 \text{ Watt} \div 62,6 \text{ Watt}) \\ &\approx \mathbf{1/3} \end{aligned}$$

of the radiant heat loss of the body $DH_{\text{RADIATION}}$ of Paragraph 1.1, amounting to somewhere between:

$$\begin{aligned} DH_{\text{RADIATION}} \times 1/7 &= 45 \text{ Watt} \times 1/7 \\ &= \mathbf{6,5 \text{ Watt}} \end{aligned}$$

and

$$\begin{aligned} DH_{\text{RADIATION}} \times 1/3 &= 45 \text{ Watt} \times 1/3 \\ &= \mathbf{15 \text{ Watt.}} \end{aligned}$$

Beside this, the face and ears have the highest density of thermoreceptors (Squire, 2009, Stevens & Choo, 1998), the face perceives thermal changes in the environment the strongest, much stronger than, for example, the vertex, the uppermost surface of the human head (Yung-Bin, Jung, Park, Lee, 2017), and, although the facial skin area is only 4 to 5% of the entire body surface, under radiant heating, the facial skin will cause 20% of the perspiration drive of the body (Nadel, Mitchell & Stolwijk, 1973).

All of the above makes it logical to make use of the disturbance of the radiation balance as a cooling method and to focus the effect of the new cooling device on the head and more specific: *The Face*.

2: Cooling systems

There are many, many methods to cool down gaseous, solid, or liquid media. An extensive chronology of the development of air conditioning and refrigeration is provided by the American Society of Heating, Refrigerating and Air Conditioning Engineers ASHRAE (Nagengast, Groff & Kraus, 2006). Some of these solely focus on *process cooling*, like the freeze-drying of food or the quenching (and drawing) of metals. Even a common home model refrigerator could be considered a process cooler.

Process coolers may use extreme temperatures, will only affect media in confined surroundings, require very specific conditions or larger amounts of free fluids and seem unsuitable for use in cooling down humans. From the chronology, some methods that use convection as cooling principle, that could be used to increase the thermal comfort of humans, and are still in use, are reviewed briefly below.

2.1 Commercial Airliner Environmental Control System (ECS)

Passenger airplanes cruise at high altitude, where the air is freezing cold. To supply passengers with enough fresh, healthy and rightly pressured air, highly heated and thus sterilized air is drawn in from the compressor stage of the jet engine(s), just before the fuel is injected. This high-temp air is then fed into an air cycle machine- some combination of a turbine and a compressor- in which the high-temp air is refrigerated with the outside, freezing cold air and compressed to keep the cabin pressurized. Intriguing as it is, it is not a suitable cooling method at ground level as freezing cold air is exactly what won't be on hand on hot summer days.

The efficiency of the system depends on many external factors and the demands of the plane itself and the plane's cabin (Hunt, Reid, Space & Tilton, 2007).

2.2 Steam Jet Cooling

Steam jet cooling is heritage from the early 1930's. Simply explained, it works like this: Steam is fed in a device, similar to the choke tube of a carburettor, to speed up the steam flow to high- even supersonic- speeds, creating a partial vacuum, perpendicular to the air stream. The vacuum draws in vapour from saturated air above a water reservoir, similar to fuel from a carburettor float chamber.

The now undersaturated air above the water in the reservoir, helped by the partial vacuum will extract water vapour from the water and will, because of the heat of evaporation, cool down the water in the reservoir that then can be used to cool down media (Shet, Sundararajan & Mallikarjuna, 2009). This system was used in steam trains and in factories where steam was (and sometimes is) a major energy carrier.

The Coefficient Of Performance (COP), the ratio of energy input and cooling power output of a modern steam jet cooler is around 0,55 (Noeres, 2005).

2.3 Vortex Tube Cooling

The Vortex tube was invented by French physicist Georges J. Ranque (US Patent 1.952.281, 1931). The patent describes a tube, in which pressurized gas is injected tangentially, creating a high-revving swirling action inside and against the wall of the tube. At the end is a conical shaped cap that allows only the outer layer of the gas to escape the tube. The rest of the gas is forced in another vortex, swirling back inside the outer vortex. There is quite some complex physics involved but in simple terms, it results in a division in a colder gas stream and a hotter air stream. Colder gas is on the utmost outer diameter of the outer vortex and can be cooled down up to a difference of 70°C. When starting with air at room temperature it results in air of -50°C. The hot air, exiting via the inner vortex to the other end of the tube, may reach 200°C. There are no moving parts; the only requirement is compressed air. Vortex tubes are now used for spot cooling where compressed air is readily available. In machine shops, they are used to cool down cutting tools during milling and lathing, eliminating the need for liquid coolants. The COP of a vortex tube is below that of compressor-based air conditioners, used in buildings (Robinson & Groll, 1996).

2.4 Stirling Cycle Refrigeration

The Stirling Cycle heat pump or refrigerator uses a constant amount of gas that undergoes two constant-temperature and two constant-volume processes during a single cycle (Spence & Foiles, 1982). They are constructed in many different ways: With pistons, turbo machinery or acoustic waves (Haywood, Raine & Gschwendtner, 2002). Many may remember a Sterling engine, constructed from single-cigar cases and paperclips, driven by a tea-warmer. When used as a cooler, the Stirling engine absorbs heat from its environment, whilst driven mechanically and may be operated, using air. Theoretically, they should perform at a very high COP but at practical, environmental temperatures, they underperform (COP 2 - 3) the compressor-type air conditioners, generally found in houses and cars (COP 3,5 - 4) (Haywood, Raine & Gschwendtner, 2002). They are however very suitable for low capacity cryogenic ($\geq -150^{\circ}\text{C}$) cooling (Tassou, 2008), implicating a large format for higher capacities.

2.5 Adsorption Refrigeration

Adsorption means, that molecules of a fluid are bound to a solid material via Van der Waals force (Ruthven, 1984). An adsorption cooler consists of an evaporator, placed in the space to be cooled, connected to an adsorber outside the room with a condenser in between. The adsorber, consisting of for example silica gel, just like the little cloth bags one finds in packages with things, sensitive to moisture, attracts the gaseous coolant, coming from the

evaporator. If the adsorber is saturated, the channel between evaporator and condenser is closed and the adsorber is heated, thus releasing the coolant to the condenser. After the condenser releases its heat to the outside world, the coolant is fed back into the evaporator. It is quite similar to a desiccant wheel. A bit primitive and the COP for the best performing coolant (methanol) is about 0,5 (Critoph, 2007). See for example EP1154208 (Patzner, 2001).

2.6 Air Cycle Refrigeration

This is a quite complicated way to produce temperatures up to 100°C under the initial value (Lewis, Chaer & Tassou, 2007) by firstly compressing a gaseous coolant (air), followed by isobaric (constant pressure) cooling, followed by expansion to the initial pressure to get a temperature drop. These systems are used in industries where the lack of chemical coolants is an advantage and the low COP (around 0,75, TNO, 2003) and noise from the compressor don't matter too much.

2.7 Magnetic Refrigeration

These work with the magnetocaloric effect: The presence of a magnetic field makes a medium warm up and the removal of the magnetic field makes the medium cool down which thus creates a cooling effect. The magnetising and demagnetising of a magnetic refrigerant is analogue to the compression and expansion in a compressor based refrigerator. It sounds quite *science fiction* but really exists. Further reading in *Design and Performance of a Permanent-Magnet Rotary Refrigerator* (Zimm, Boeder, Chell, Sterberg, Fujita, Fujieda & Fukamichi, 2006). The highest reported COP is 2,4 for near room temperatures, a bit low compared to compressor based refrigerators (Okamura, Yamada, Hirano & Nagaya, 2006).

2.8 Thermoelectric Refrigeration

This is based on the Peltier effect: An electric current through the junction between two different materials causes the junction to warm up or cool down, dependent on the direction of the electric current. Peltier elements themselves are solid state, flat and sheet shaped: 3 - 5 mm thickness on average but often will require a finned heat sink (Laird, 2010).

At a temperature difference of 10°C and at 10% of its maximum rated current, the COP of a Peltier element will be around 2,7, steadily decreasing to a COP of 0,6 and lower at 30°C and 30% of its maximum current. A Peltier element is very inefficient, usually small and not a cheap solution (Meerstetter, 2018).

The cooling methods from 2.1 - 2.8 each have a distinct disadvantage. Table 3 on page 22 gives an overview.

Table 3*Summary of reviewed cooling methods*

§	cooling method	distinct disadvantage	COP
2.1	ECS	Need for cold air	N/A
2.2	Steam Jet	Need for steam	0,55
2.3	Vortex Tube	Need for compressed air	N/A
2.4	Stirling Cycle	Large or low capacity	2 - 3
2.5	Adsorption	Need for heating	0,5
2.6	Air Cycle	Large, noisy and inefficient	0,75
2.7	Magnetic	Sci-Fi, not readily available	2,4
2.8	Thermoelectric	Inefficient at higher power	0,6 - 2,7

From Paragraphs 2.1 - 2.8.

In the cited literature, compressor based air conditioners are mentioned without explanation, probably because they are considered generally known. Compared to the methods reviewed above they are more efficient with a COP of 3,5 - 4 (Haywood, Raine & Gschwendtner, 2002).

The car A/C and the portable air conditioner, mentioned in the introduction are usually compressor based. The actual cooling is generated by the evaporation of a liquefied coolant. The then gaseous coolant is compressed and cooled down to a liquid and then again evaporated in a closed system.

3: Compressor based cooling systems

Compressor based air conditioners generally blow a stream of cold air into a room (the *occupied space*) to cool down the air temperature to make its occupants more comfortable by cooling them by convection.

Figure 1 shows on the left the cooling half of the cycle of these cooling systems, where a liquid refrigerant is evaporated in a heat exchanger (blue). The evaporation extracts heat from the heat exchanger because of the enthalpy of vaporization. Think of Eau de Cologne, evaporating from your skin. Then a flow of ambient air, indicated with the red-and-blue arrows, pointing to the left, is fed through the heat exchanger, and exchanging heat which gives a cooled down airflow, indicated with the blue arrows. The colder air lowers the ambient temperature of the occupied space and cools down its occupants via convection. The temperature of the cooled down air may reach 4°C and below at low air speeds on a 30°C day (Jaguar Cars Ltd, 2014).

On the right the second half of the cycle: The evaporated refrigerant is compressed to a liquid again and then cooled down in yet another heat exchanger that debouches to the outside world. The heat is 'pumped' from inside to outside.

Figure 1. The closed cycle of a compressor based air conditioner (After Noé Lecocq, 2007).

Portable air conditioners often have a drawer-like container to collect water that condenses to the cold heat exchanger. Under a stationary car, there often is a puddle, also from the condensed water. This is because cold air can contain less water than hot air by law of nature. The air that enters the occupied space is thus dehumidified and 'dry'. In cars, the A/C is therefore even used on cold days to dehumidify the air to prevent the windows from frosting. Indeed, the air is firstly cooled down and then heated (Jaguar Cars Ltd, 2014).

In stationary situations (buildings), two kinds of compressor-based systems are found:

- Stand-alone systems that are mounted in, for example, a window frame to be able to release heat, taken from the inside, to the outside world or having an air duct to the outside world for the same purpose.
- Split systems, where the heat releasing part is mounted outside and the cooling part is on the inside of the room.

Figure 2. Left a Tristar stand-alone air conditioner (Tristar, 2018), right the components of a Mitsubishi split system (Bol.com, 2018).

Both systems are common in homes and smaller businesses. In larger buildings, the inside part of the split systems will often be integrated in the ceiling of the room, the ducting hid from view by the ceiling. In means of transport functionally similar systems are used, its components almost always hidden from view.

More in detail, the system works like this:

In the cool part of the air conditioner, the heat exchanger is called the evaporator and looks like a car radiator. Just before entering the evaporator, the liquefied and pressurized coolant is released with a valve. The release of the pressure of the liquid coolant causes it to boil and vaporize in the evaporator. The vaporization is endothermic and extracts the required heat from the evaporator.

The vapour leaves the heat exchanger and is ducted to a compressor (the crossed black square in Figure 1).

In the compressor, the vaporized and heated up coolant is compressed to a liquid again and pumped into the red heat exchanger, another radiator like part, called the condenser, where the heat is released to the outside world via convection or active ventilation.

The heat uptake from the cold heat exchanger (the refrigerating capacity or cooling power) is larger than the effort it takes to compress the coolant to a liquid again, that is how the efficiency, the COP of the system can be higher than 1 (or 100%).

Depending on the relative humidity (RH) of the ambient air, condensation forms onto the cold evaporator. Figure 3 shows, how much water air of a certain RH and temperature contains.

Figure 3. The relation between RH, air temperature in °C and the mass of water vapour in g / m^3 of air (Eidelloth, 2009).

For example: If ambient air of 30°C and 70% RH (the red lines) is cooled down to the earlier indicated 4°C and 100% RH (the light blue lines), it has to lose $(21 - 6 =) 15 \text{ g}$ water per m^3 of air (the dark blue line on the right).

These compressor-based systems do have a downside: The coolant used generally is not environmentally friendly. This is not a problem as long as the system is airtight but often, there is some leakage.

Older systems use Dichlorodifluoromethane (R12), which enlarges the hole in the ozone layer when released. Modern coolants such as 1,1,1,2-Tetrafluoroethane (R134a) are better yet still aren't environmentally friendly (Montreal Protocol, 1987 - 2016). Especially in non-static applications the systems leak considerably, about 7% per year (Reiss, March 1996).

The COP of these systems is limited by the enthalpy of vaporization of the coolant and the mechanic and electric efficiency of the system. The higher the enthalpy of vaporization, the more efficient the system can be.

In means of transportation, the COP will typically be 2 - 3. In buildings the COP may reach 4 to 5 because there is enough space to create efficiency and gains in energy consumption (Uges, 2012-2015).

To avoid the use of these environmentally unfriendly coolants, manufacturers have been developing systems, using carbon dioxide (CO₂) as coolant. CO₂ is not entirely environmentally friendly, yet- considering the small amount needed- will have little impact on the environment compared to the more generic coolants. The pressure needed to liquefy CO₂ is much higher than for the generic coolants, making it difficult to keep the system gas-tight. Furthermore, the heat of vaporization of CO₂ is relatively low, lowering the COP of these systems to < 2 (Urieli, 2010).

Table 4 gives an overview of the discussed refrigerants.

Table 4

Common refrigerants, their enthalpy of vaporization, and density

refrigerant	enthalpy of vaporization (kJ / kg)	liquid density (kg / l)
Dichlorodifluoromethane (Freon®, R12) ¹	352,8 (at 0°C)	1,40
1,1,1,2-Tetrafluoroethane (R134a) ²	398,8 (at 0°C)	1,03
CO ₂ ³	234,5 (at 0°C)	1,03
C ₂ H ₅ OH (ethanol, Eau de Cologne) ⁴	841,0	0,79
H ₂ O (water, sweat on the human skin) ⁵	2.260,0	1,00

¹ Data from DuPont Freon Document RWJ306, July 2005; Freon is a registered trade name of DuPont Chemical; ² Data from DuPont Suva refrigerants, document 232448, October 2004;

³ Data from Wittemann DataProp1003, 2016; ^{4, 5} Data from BINAS, Table 11, 1998.

As written, even R134a is not very environmentally friendly and is eased out gradually and replaced with similar performing yet environmentally friendlier refrigerants.

4: Water based cooling systems

As Table 4 showed, water has an enthalpy of vaporization over 5x higher than R134a and is very environmentally friendly.

Several manufacturers produce water-based air conditioners. The enthalpy of vaporization is used, either to cool down the air directly or indirectly via a heat exchanger.

The dew point, the temperature to which the ambient air must be cooled to get to a 100% relative humidity (RH)- when the air is saturated with water and evaporation is inhibited- is the lowest temperature these systems can theoretically reach (Urone & Hinrichs, 2017).

This is why these systems are often called dew point coolers.

In reality, a dew point cooler will never cool down the air to the dew point, as this would imply 100% efficient evaporation and 100% conductivity of the materials used.

When air is cooled down below the dew point, condensation will occur. This happens- for example- to the cold part, the evaporator of the compressor based air conditioners in Chapter 3 and to a cold drink in the summer: Air close to the glass will cool down below the dew point and condensation to the glass of the drink will occur.

From Figure 3, this temperature can be determined. Start at the intersection of the ambient situation, for example air of 30°C and 70% RH and follow the green lines: Go horizontally to the left to the intersection with the far left bold curve, indicating 100% RH. Then go down vertically. The corresponding temperature is the dew point. In this example it is about 23,5°C. From the graph in Figure 3 it is quite easy to see, that air, cooled down to the dew point is not much cooler than the ambient air except on days with very low relative humidity. This implicates, there must be a considerably larger airflow than with the generic air conditioners to reach the same inside temperature.

From the HX Diagram, shown in Figure 4 on the next page, the dew point can be looked up too. In Table 5 the look-up value of the dew point of respectively an average Dutch summer day, a hot Dutch summer day and the summer days on which the perception tests, described in Chapter 12 were performed.

Table 5
Dew point under different conditions

air temperature	relative humidity (RH)	dew point ¹
27°C ²	77%	22,5°C
33°C ³	60%	24,0°C
30°C ⁴	30%	10,5°C

¹ Dew point from Figure 4: HX Diagram; ^{2,3} Data from KNMI, 2018; ⁴ Values of the test days in Chapter 12.

Figure 4. HX Diagram (Bravenec, 2017, translated to English).

To get to the right value, this is how to do it, taking the last day in Table 5 (30°C and 30% RH) as an example:

Start at 30°C and follow the red line until the curve of 30% RH

From the intersection, follow the green line to the curve of 100% RH

Follow the blue line to the corresponding temperature

Figure 5. Repeated and *sketched-in* HX Diagram (Bravenec, 2017).

With the HX Diagram on hand, different layouts of evaporative cooling systems can be assessed.

Direct evaporative systems make direct use of the enthalpy of vaporization: In Figure 6, water is dripped over an air permeable material, and is exposed to a flow of ambient air, indicated with the red-and-blue arrows. The evaporation of the water extracts heat and makes the air cool down and humidifies it. This layout is very uncomplicated.

Figure 6. Direct evaporative cooling.

The humidification of the inside air- the opposite effect of generic air conditioners which extract water from the air by condensation as explained in Chapter 3 (remember the 4°C mentioned there)- may be disadvantageous.

Indirect evaporative systems make use of some form of a heat exchanger, shown in Figure 7. In simple terms, water evaporates from the wetted side of a wall into the left-to-right airflow, indicated with the blue-and-red arrows, which makes the wall cool down. A second, right-to-left airflow, indicated with the red-and-blue arrows comes in contact with the opposite side of the cooled down wall, cools down and is brought in the occupied space (blue arrows).

Figure 7. Indirect evaporative cooling.

The above systems focus on convection rather than radiation.

Water based systems that alter the radiation balance also exist: So called climate ceilings are heat conductive and have water pipes meander over them. The water in these pipes is cooled down by means of a compressor-based cooling machine, situated outside the building. These climate ceilings do not make use of the high enthalpy of vaporization of water.

For instance Inteco BV (2011 - 2018) claims a cooling power of 60 - 80 W / m² of climate ceiling at an initial water temperature of 15°C. Manufacturers of climate ceilings depend on air of low relative humidity (RH) in the occupied space, sometimes helped by dehumidifiers, to avoid condensation to the ceiling as the cooled down water may cause the ceiling to cool down below the dew point.

The relatively large distance between ceilings and humans- especially when seated- mean, that the needed viewing angle to get the desired effect requires a large cooled ceiling area.

Figure 8. Climate ceiling.

The above paragraphs only cover the outline of water based cooling. Below the further explanation and calculations.

4.1 Vaporization and evaporation

Water will boil and vaporize to steam at 100°C under normal air pressure. Still, the streets will get dry after a rain shower without the pavement reaching 100°C. This is called evaporation.

Encyclopedia Britannica defines vaporization (n.d.), as

Vaporization, conversion of a substance from the liquid or solid phase into the gaseous (vapour) phase. If conditions allow the formation of vapour bubbles within a liquid, the vaporization process is called boiling.

Encyclopedia Britannica defines evaporation (n.d.), as

Process by which an element or compound transitions from its liquid state to its gaseous state below the temperature at which it boils; in particular, the process by which liquid water enters the atmosphere as water vapour. Evaporation, mostly from the sea and from vegetation, replenishes the humidity of the air. It is an important part of the exchange of energy in the Earth-atmosphere system that produces atmospheric motion, and therefore weather and climate. The rate of evaporation depends on the temperature difference between the evaporating surface and the air, the relative humidity, and wind.

The active method of human heat loss, sweating, works with the enthalpy of vaporization: Drops of sweat will evaporate from the skin, extracting 2.260 kJ / kg of sweat. Alcohol (ethanol, C_2H_5OH) in Eau de Cologne will boil at 78°C and has an enthalpy of vaporization of 841 kJ / kg. The alcohol will, because of the lower boiling point, evaporate more easily from your skin, giving a direct cool sensation but will, because of the lower enthalpy of vaporization, extract less heat per kg of product than water.

The human body needs to actively lose up to 1.000 Watt of generated heat during, for example, a bicycle race. The airstream around the cyclist will allow enough sweat to evaporate. When coming to a stop, the evaporation will almost come to a halt, causing the sweat to form visible drops or even streams (University of Notre Dame, 2003, Silverthorn, 2013).

In fact, the air, directly surrounding the bicycle racer, will be saturated immediately (remember the cold drink), unable to take up vapour to cool down the cyclist sufficiently. During the race, this will not occur: Then there is a constant flow of fresh, unsaturated air surrounding the cyclist's body.

In most water-based air conditioning systems, water (just as sweat) is sacrificed in the process of evaporation, making some form of water supply necessary. In larger systems, a (semi-)continuous flow of tap water may be used, smaller systems may use a container. This may or may not be a disadvantage. At least, water is very environmentally friendly.

The higher the enthalpy (or heat) of vaporization, the more effective a coolant will be. Existing water based cooling systems outperform compressor based air conditioners in efficiency, with a claimed COP of 15 - 20 (Amer, Boukhanouf & Ibrahim, 2015) which seems credible, considering the higher enthalpy of vaporization of water and the mechanical simplicity of these systems.

4.1 Direct evaporative coolers

Direct evaporative coolers make direct use of the enthalpy of vaporization. These systems intrinsically humidify the air substantially. In some circumstances, this can be an advantage over compressor-based air conditioners that dehydrate the air. Referring to Figure 3 and 4 it will be clear, that the efficacy of direct evaporative cooling depends on temperature and relative humidity.

Figure 9 shows the process more in depth. It is the basis for Figure 6.

Figure 9. Direct evaporative coolers (Kelley, 2013).

The Tristar stand alone air conditioner, comparable to the one on the left in Figure 2, model 5490, delivers 6.000 BTU / h or 1.750 Watt of cooling power (Tristar, 2018).

With this value as a starting point and using advantageous circumstances (dry and hot air, 35°C and 30% RH and perfect 100% efficiency), the theoretical capacity of a direct evaporative cooler can be calculated.

According to Figure 3, air of 35°C and 30% RH contains 12 g / m³ of water vapour. At 35°C and 100% RH this is 40 g / m³.

This implies, 1 m³ of untreated air can take up (40 - 12 =) 28 g or 0,028 kg of water vapour, not considering the change in temperature of the treated air.

The evaporation of 28 g water per m³ of air gives a cooling energy of:

$$E_{28 \text{ g water} / \text{m}^3} = m \times \text{enthalpy} / \text{m}^3 = 0,028 \text{ kg} / \text{m}^3 \times 2.260 \text{ kJ} / \text{kg} = \mathbf{63.280 \text{ Joule} / \text{m}^3}$$

The volume of air per second, needed to match the 1.750Watt (Watt = J / s) cooling power of the Tristar A/C is

$$\begin{aligned} V_{\text{air } 1.750 \text{ Watt} / \text{s}} &= P_{\text{Tristar}} \div E_{28 \text{ g water}} / \text{m}^3 = 1.750 \text{ J} / \text{s} \div 63.280 \text{ J} / \text{m}^3 \\ &= \mathbf{0,0277 \text{ m}^3 / \text{s}} \text{ (27,7 litres / s or 1,66 m}^3 \text{ / minute)} \end{aligned}$$

Air has a specific mass of 1,293 kg / m³ and a specific heat of 1,0 kJ / kg / K (BINAS, 1998). This implies a temperature change of:

$$\begin{aligned} -\Delta T_{63.280 \text{ J}} &= E_{28 \text{ g water}} / \text{m}^3 \div (\text{specific mass} \times \text{specific heat of air}) \\ &= 63.280 \text{ J} \div (1,293 \text{ kg} / \text{m}^3 \times 1,0 \text{ kJ} / \text{kg} / \text{K}) \\ &= 63.280 \div 1.293 \\ &= \mathbf{48,9K} \text{ (~ 49°C colder)} \end{aligned}$$

Which, of course is impossible. This cold air cannot contain this much water.

Let’s try a different approach and assume, the cool, humid air is cooled down to 20°C and then has a RH of 100%, equaling 17 g of water vapour per m³ of air, only (17 - 12 =) 5 g of water can be diluted, extracting (0,005 kg x 2.260 kJ / kg =) 11.300 J, resulting in 0,155 m³ (or 155 litres) of air per second or ~ 10 m³ of air per minute. A simple cooker hood easily flows 250 m³ per minute (IKEA, 2015) so 10 m³ is an acceptable airflow.

On day 2 of Table 5, the hot summer day (33°C and 60% RH), a m³ of air contains 22 g of water vapour, the same amount as air of 24°C and 100% RH, the corresponding dew point. If only 5 g / m³ evaporates (making 22 + 5 = 27 g water vapour / m³ of air), the lowest temperature that can be reached, that is at a RH of 100%, the air will then cool down to 28°C. That’s not very cool.

Table 6
Mass of water vapour per m³ of air

air temperature	relative humidity (RH)	mass of water vapour / m ³
33°C (starting point ¹)	(starting point ¹) 60%	(from Figure 3) 22 g
24°C (value from Figure 3, again 22 g and RH =)	100%	(the dew point) 22 g
28°C (value from Figure 3, 27 g & 100% RH)	100%	(22 g + 5 g =) 27 g

¹ From Table 5.

These calculations, although very rough, show that this kind of cooling may be efficient in terms of airflow and water use but needs very dry air to get the *Cool, Humid Air* on the right in Figure 9 to a temperature, comparable to the air temperature of compressor based air conditioners.

4.2 Indirect evaporative coolers

Indirect evaporative coolers avoid the increase of *absolute* humidity (water uptake) of the air.

Figure 10. Model of indirect evaporative cooling (Western Environmental Services Corporation, 2015).

The *Indirect* part and the *Secondary air stream* in the model will be outside the occupied space. The *Cool air* will debouch into the occupied space.

A large area of heat-conducting material is moistened with water on one side and exposed to the secondary air stream. The evaporation of the moisture will cause the area of heat-conducting material to cool down.

The other, dry and now cooled down, side of this heat-conducting material is exposed to the *Primary air stream*, causing the primary air stream to cool down. The model suggests multiple layers of heat-conducting material, as is the case in real-world applications. To reach enough cooling capacity, a large area heat exchanger and a large primary and secondary air stream are essential.

In practice, the airflows are not entirely separate: Fresh, outside air is blown into the large area heat exchanger, the *warm air*. A part of this *primary air stream* enters the occupied space. The rest of the primary air stream is used as the secondary air stream and will be cooled down by humidification through evaporation and hence which cool down the heat exchanger. This air will exhaust to the outside. After the process is started, the outside air is cooled down in the primary air stream and cool air enters the occupied space (Kouwenhoven, Huizinga, Bootsvelde, Janssen, & Uges, 2007).

Figure 11 gives an idea of the size of an indirect cooling system. It is the dew point cooler annex displacement ventilator for a small size sports hall. The 3 heat exchangers per unit are made of two-wall polypropylene sheets that resemble corrugated cardboard with an area of $1 \times 1,38 \text{ m}^2$, stacked to 63 layers to get enough heat exchanger area (RCC, 2008, StatiqCooling, 2009). It cools down the air by a maximum of 8K or 8°C with a COP of 12. The airflow is ducted through air socks, flexible air channels made of fabric, that run alongside the ceiling of the hall and exits *hard* (Lobrecht, 2009) through nozzles in the air socks, to make sure, the fresh air reaches the lower part of the sports hall. It is directed to the lower two metres of the hall with an airflow of cooled down air of $8.400 \text{ m}^3 / \text{h}$ or 2.000 litres per second (SenterNovem, 2009).

Figure 11. A dew point cooler for a sports hall (Thermo Air, 2008).

In the introduction, I stated, I want to combine *the most effective* way to cool down a human with *the most efficient* cooling method and that the result- apart from being effective- must be simple, silent, virtually windless, energy-efficient, environmentally friendly, inconspicuous, comfortable and healthy.

In Chapter 1, I reasoned, the most effective way is to focus on altering the radiation balance and focus on the human head (or better still: *The face*). The radiation balance is only used in the climate ceiling. The compressor based air conditioners and the systems that use water evaporation all use convection and relatively large air streams. Still, the methods that use the evaporation of water do have the best COP and hence are the most efficient.

5: The new cooling device

The basic idea for the new cooler was to use the space between the roof and the ceiling of a car to cool down its cabin. It is comparable to only one sheet of the heat exchangers, shown in Figures 7 and 10, and using it inside instead of outside. The cooling capacity turned out to be very low, which is confirmed by the specs of the dew point cooler of Figure 11.

But, as Chapter 1 showed, it could well be, that altering the radiation balance may provide a cooling effect on humans without having great impact on the ambient temperature.

If the device is placed close to the head or even better: *The face*, the viewing angle can be as large as in the climate ceilings from page 31 in Chapter 4 without the need for a large heat-exchanging area.

Using the evaporation of water would result in a high COP and very little impact on the environment.

If this one layer is sufficient to get the desired cooling effect, the energy saving will be huge: Only little cooling power would be needed. Cooling power stemming from a system with a high COP.

The design task is to combine these elements in a clean, uncomplicated product.

lowered ceiling element

or table top cooler

the same viewing angle
from a smaller area

Figure 12. One layer of an indirect dew point cooler, placed close to the human's head.

The theoretic maximum cooling power can be calculated according to the Stefan-Boltzmann law, used for the black body head in Chapter 1:

$$\begin{aligned} E &= \sigma T^4 \\ E_{\text{cooling power}} &= E_{\text{ambient}} - E_{\text{dew point}} \end{aligned}$$

Table 5 gave the temperature, RH and dew point of respectively an average summer day, a hot summer day and the summer days on which the perception tests, described in Chapter 12 were performed. From these values, the theoretic maximums of cooling power per m² of heat exchanger are calculated.

Situation 1: Air temperature 27°C / 300,15K, dew point 22,5°C / 295,65K.

$$\begin{aligned}
 E_{300,15K} &= 5,670 \times 10^{-8} \times 300,15^4 = 5,670 \times 10^{-8} \times 8,11 \times 10^9 \\
 &= 460 \text{ W / m}^2 \\
 E_{295,65K} &= 5,670 \times 10^{-8} \times 295,65^4 = 5,670 \times 10^{-8} \times 7,64 \times 10^9 \\
 &= 433 \text{ W / m}^2 \\
 E_{\text{cooling power s. 1}} &= E_{300,15K} - E_{295,65K} = 460 \text{ W / m}^2 - 433 \text{ W / m}^2 \\
 &= \mathbf{27 \text{ W / m}^2}
 \end{aligned}$$

Situation 2: Air temperature 33°C / 306,15K, dew point 24,0°C / 297,15K.

$$\begin{aligned}
 E_{306,15K} &= 5,670 \times 10^{-8} \times 306,15^4 = 5,670 \times 10^{-8} \times 8,79 \times 10^9 \\
 &= 498 \text{ W / m}^2 \\
 E_{297,15K} &= 5,670 \times 10^{-8} \times 297,15^4 = 5,670 \times 10^{-8} \times 7,80 \times 10^9 \\
 &= 442 \text{ W / m}^2 \\
 E_{\text{cooling power s. 2}} &= E_{306,15K} - E_{297,15K} = 498 \text{ W / m}^2 - 442 \text{ W / m}^2 \\
 &= \mathbf{56 \text{ W / m}^2}
 \end{aligned}$$

Situation 3: Air temperature 30°C / 303,15K, dew point 10,5°C / 283,65K.

$$\begin{aligned}
 E_{303,15K} &= 5,670 \times 10^{-8} \times 303,15^4 = 5,670 \times 10^{-8} \times 8,45 \times 10^9 \\
 &= 479 \text{ W / m}^2 \\
 E_{283,65K} &= 5,670 \times 10^{-8} \times 283,65^4 = 5,670 \times 10^{-8} \times 6,47 \times 10^9 \\
 &= 367 \text{ W / m}^2 \\
 E_{\text{cooling power s. 3}} &= E_{303,15K} - E_{283,65K} = 479 \text{ W / m}^2 - 367 \text{ W / m}^2 \\
 &= \mathbf{112 \text{ W / m}^2}
 \end{aligned}$$

In summary:

Table 7

Cooling power per m² under different conditions as per Stefan-Boltzmann

ambient circumstances	dew point	cooling power per m ²
27°C / 77% RH	22,5°C	27 Watt
33°C / 60% RH	24,0°C	56 Watt
30°C / 30% RH	10,5°C	112 Watt

These are high values, compared to the heat loss break down in Table 1 but low, compared to the cooling power of a convection-based air conditioner. Dry air- with a low relative humidity (RH)- improves the cooling power vastly.

In human physiology, ambient temperatures between 5°C and 20°C, are called metabolic: The BMR maintains the body temperature. From 20°C to 30°C is considered thermo-neutral. Above 26°C, the comfort point, humans start sweating actively, albeit unnoticeable at first (Guyton & Hall, 1996, Kempisty, 2006, Paulev & Zubieta-Calleja, 2004). See the graph below.

Figure 13. Heat loss of the human (after Paulev & Zubieta-Calleja, 2004).

X-axis (horizontal):	Environmental temperature;
Y-axis (vertical):	Heat loss of the human in Watt;
Black curve:	Generated metabolic heat;
Red curve:	Dry heat loss (radiation, convection and conduction);
	Dry heat uptake above 37°C;
Green curve:	Perspiration with above 26° (the comfort point):
	Active sweating;
Light blue curve:	-5 Watt difference in the radiation balance;
Dark blue curve:	-15 Watt difference in the radiation balance.

The graph shows, that a difference of 5 Watt to 15 Watt in radiation balance- the downward shift of respectively the light and dark blue curve relative to the green curve- renders a reduction of 3°C to 6°C in *operative temperature*, indicated with the light and dark blue vertical lines.

Operative temperature or dry resultant temperature is the temperature, caused by air temperature and radiant temperature (ISO 7726 (1998 - 10)), the temperature for *things*. It is not the *wind chill*, which takes the air speed and relative humidity into account, the temperature *perceived* by beings.

Put simple, a room with an air temperature of 28 - 32°C will physiologically be as a room of 26°C, exactly the comfort point, if an extra 5 - 15 Watt of heat can be lost by an individual. Active sweating should stop.

An area of 1/3 m² of single layer heat exchanger theoretically already delivers 9 - 15 Watt of cooling power if it could reach the dew point to a possible maximum of 37 Watt. In actual practice it never will, as this would again imply 100% efficacy of the evaporation process and perfect heat-conduction of the material of the wall. The cooling power will therefore be less than calculated but only 50% of the theoretical cooling power already suffices.

A possible disadvantage, mentioned at the direct evaporative cooler (Paragraph 4.1, page 33) could be the increase in RH because the single layer debouches to the room itself.

The theoretical maximum addition of water vapour can be calculated from the cooling power and the enthalpy of water.

The mass m of water consumption per hour theoretically follows:

$$m_{\text{water}} / \text{h} = (\text{cooling power} \div \text{enthalpy of vaporization}) \times 3.600 \text{ s}$$

1/3 m² of cooling device area will suffice.

Hence, the cooling power in Table 7 is 1/3 of the cooling power of Table 6.

Table 8

Water consumption per 1/3 m² under different conditions

cooling power	enthalpy of vaporization	water consumption
9 Watt (J / s), 1/3 of 27 Watt	2.260 J / g	14 g / h
19 Watt (J / s), 1/3 of 56 Watt	2.260 J / g	30 g / h
37 Watt (J / s), 1/3 of 112 Watt	2.260 J / g	59 g / h

To get an impression of the influence on the RH, the values of the second line (30 g / h, 33°C, 60% RH) were used to calculate the increase of RH in a *worst case scenario*: A tiny classroom, no longer allowed since 1999.

Before the introduction of the Dutch Arbeidsomstandighedenwet framework law on March 18, 1999, worse circumstances were allowed for primary school class rooms (Ministeries of O&W & M. & S.Z. & W., 1989). These are used for the calculations: The smallest allowed primary school classroom had a floor area of 42 m² x 3 m height; The maximum allowed number of pupils was 35 and the lowest allowed ventilation per person was 20 m³ / h / pupil. All pupils are assumed to be equipped with 1/3 m² of single sheet cooler.

The heat loss of 35 small persons would roughly be half of the values as per Table 1. Of interest is the evaporation, 22,5 Watt for a naked human and half of that (10,5 Watt) for a pupil as this too contributes to the RH. It again follows:

$$m_{\text{water} / \text{h}} = (\text{cooling power} \div \text{enthalpy of vaporization}) \times 3.600 \text{ s}$$

$$\begin{aligned} m_{\text{pupil}} &= (10,5 \text{ J} / \text{s} \div 2.260 \text{ J} / \text{g}) \times 3.600 \text{ s} \\ &= 16,7 \text{ g} / \text{h} \end{aligned}$$

for a total of

$$\begin{aligned} m_{35 \text{ pupils}} &= m_{\text{pupil}} \times 35 \\ &= \mathbf{585 \text{ g} / \text{h}} \end{aligned}$$

The 35 cooling devices add 30 g / h a piece, for a total of 35 x 30 g / h

$$m_{35 \text{ coolers}} = \mathbf{1.050 \text{ g} / \text{h}}$$

The minimum ventilation volume V is 20 m³ / h / pupil, in total 35 x 20 m³ / h

$$V_{35 \text{ pupils}} = \mathbf{700 \text{ m}^3 / \text{h}}$$

The increase of water vapour per m³ of vented air follows mass / volume:

$$\begin{aligned} &= (585 + 1.050) \div 700 \text{ m}^3 / \text{h} \\ &= 1.635 \div 700 \text{ g} / \text{m}^3 \\ \Delta m_{\text{pupils} + \text{devices}} &= \mathbf{2,3 \text{ g} / \text{m}^3} \end{aligned}$$

According to Figure 3, air of 33°C and 100% RH can contain 37 g / m³ of water vapour. 60% of that is 0,6 x 37 g / m³

$$m_{\text{vapour } 33^\circ\text{C} / 60\% \text{ RH}} = \mathbf{22,2 \text{ g} / \text{m}^3}$$

The humidified air will contain $22,2 + 2,3 = 24,5 \text{ g / m}^3$, caused by pupils and cooling devices. The corresponding RH is $(24,5 \div 37) \times 100\%$

$$\text{RH}_{\text{pupils + devices}} = \mathbf{66\%}$$

Without cooling devices, the humidified air will contain $22,2 + 0,84 = 23 \text{ g / m}^3$. The corresponding RH is $(23 \div 37) \times 100\%$

$$\text{RH}_{\text{only pupils}} = \mathbf{62\%}$$

The cooling devices add an extra 4% to the relative humidity that in total still only increases by 6%.

Even without any ventilation, the cooling devices have a bearable impact on the RH. If 35 cooling devices would work 1 hour in a completely unventilated minimum sized classroom of $42 \text{ m}^2 \times 3 \text{ m}$

$$V_{\text{minimum classroom}} = \mathbf{126 \text{ m}^3},$$

$1.050 \text{ g / } 126 \text{ m}^3$ of water vapour would be added to every m^3 of air

$$m_{\text{added vapour / m}^3} = \mathbf{8,3 \text{ g}}.$$

The humidified air would then contain $22,2 + 8,3 = 30,3 \text{ g / m}^3$. The corresponding RH is $(30,3 \div 37) \times 100\%$

$$\text{RH}_{\text{unventilated}} = \mathbf{82\%}$$

These values imply, that $1/3 \text{ m}^2$ of single layer cooling power should indeed be enough to comfortably cool down a human to perceive the comfort point on a day, with an air temperature well above the comfort point.

The next chapter describes the first *proof of concept*.

6: The first test

Constructed of a tin bookshelf ($l \times b \times h = 70 \times 30 \times 3 \text{ cm}^3$), a tea towel to retain the water, a plastic briefcase and a fan with adjustable speed, a lab model was built to test the efficacy- if any- of the single sheet cooler.

Figure 14. Lab model of a single sheet cooler; the bookshelf is the bottom.

The lab model was tested on a hot day at $\sim 31^\circ\text{C}$ and $\sim 65\%$ RH (dew point of $\sim 23^\circ\text{C}$). After the water was allowed to heat up, an Ebro TLC1598 thermometer showed that the surface temperature of the tin bookshelf was $31,8^\circ\text{C}$. Within 3 minutes of forced ventilation, the surface temperature already dropped to $23,9^\circ\text{C}$, close to the dew point. According to Chapter 5, this should be enough to get the desired cooling effect so the concept should work.

The tin bookshelf got far too cold to feel comfortable in contact with the skin. This is attributed to the high thermal conductivity of the tin bookshelf and should be avoided for a table top cooling device as it is the object to come to a *more comfortable* way of refrigeration than the cold air stream from a compressor based air conditioner.

ISO 7730:2005 (2005, 11) teaches that more aspects than the temperature and the RH of the air in the environment affect humans in terms of comfort. It describes thermal comfort as:

That condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation.

ISO 7730 describes 13 aspects that influence thermal comfort. On 6 of these, the new cooling device may have an influence: The air temperature and The relative humidity, already addressed in Chapter 5; The vapour pressure, a look-up value in the HX Diagram (Figure 4); The sound level, The average radiation temperature and The relative speed of the airflow.

The other aspects, not directly influenced by the new cooling device, are: The level of activity; The thermal resistance of clothes; The gaseous composition of the air, The scent and smell of the air; The amount of dust in the air; The light level and The mental condition of the human.

The conductivity is not mentioned yet still does have an influence that should be avoided. In the heat breakdown of a human, summarized in Table 1, conduction was to be neglected. In the lab model, it cannot.

The lab model in Figure 14 produces, according to the specs of the fan, up to 47 dB (A) at a flow rate of 80 m³ / h (Conrad, 2010). This is the sound level at one metre distance. The device will be closer to the ears and therefore be louder, somewhere in the Average range (Ego, 2014):

46 - 65 dB (A), Average. *If you are walking down the street in a small town, this is about the decibel level of the sound you would hear. Regular conversation, the sound of a bubbling stream, and the meow of your cat might generate sound that falls in the 45 - 65 decibel range.*

In the next stage of development, the air stream and the fans producing it should be carefully considered. The continuous noise of a bubbling stream or a meowing cat seems (too) loud. Furthermore, a flow rate of 80 m³ / h for a single layer of heat exchanger of less than 0,25 m² seems very high compared to the specs of the dew point cooler for a sports hall in Figure 11, which had 8.400 m³ / h for 1.000 m² of much narrower channeled heat exchanger. The (subjective) observation is, that the fan indeed causes a large airstream. The contribution of the cooling device to the average radiation temperature is also still to be assessed.

My subjective observation, when I sat down under the cooling device (to avoid the discomforting conduction), was that I stopped sweating actively.

7: The points of departure

The first real design should be:

- Focusing on altering the radiation balance;
- Close to the human and preferably: *The face*;
- With a high COP (which implies: Water based);
- Uncomplicated;
- + Without local thermal discomfort caused by radiant temperature asymmetry, draught and vertical air temperature differences and
- + With thermal comfort (two new requirements from ISO 7730:2005).

With the day of 33,0°C, 60% RH, the tiny and crowded class room, and ISO 7730:2005 as a starting point, the influence of the cooling device on the relevant 6 aspects of thermal comfort, mentioned on page 44 in Chapter 6, are now assessed in Paragraphs 7.1 - 7.6 and summarized in Table 12.

7.1 Air temperature

Air has a specific heat of 1,0 kJ / kg / K and a specific mass of 1,293 kg / m³ (BINAS, 1998). So it takes 1.293 J to heat up 1 m³ of air by 1K (or 1°C).

The cooling power of 35 cooling devices, taken as purely convective and contributing to the air temperature, at the desired maximum of 15 Watt

$$\begin{aligned} E_{\text{cooling power 35 dev.}} &= 35 \times 15 \text{ watt} = 525 \text{ Watt} = 525 \times 3.600 \text{ J / h} \\ &= \mathbf{1.890 \text{ kJ / h}} \end{aligned}$$

The cooling power per m³ of minimal ventilation

$$\begin{aligned} E_{\text{cooling power / m}^3} &= E_{\text{cooling power 35}} \div V_{35 \text{ pupils}} \text{ (from Chapter 5)} \\ &= 1.890 \text{ kJ / h} \div 700 \text{ m}^3 / \text{h} \\ &= \mathbf{2.700 \text{ J / m}^3 \text{ or } 2,7 \text{ kJ / m}^3} \end{aligned}$$

The temperature *decrease*, caused by the 35 devices

$$\begin{aligned} -\Delta t_{35 \text{ devices}} &= E_{\text{cooling power / m}^3} \div (\text{specific heat} \times \text{specific mass of air}) \\ &= (2.700 \text{ J / m}^3) \div (1.293 \text{ J / °C / m}^3) \\ &= \mathbf{2,08^\circ\text{C}}. \end{aligned}$$

Similarly calculated, the heating power of 35 pupils, contributing to the air temperature, follows:

$$\begin{aligned} E_{\text{heating power 35 p}} &= 35 \times (0,5 \times \text{convective heat loss of a human as per Table 1}) \\ &= 35 \times (0,5 \times 25 = 12,5) \text{ Watt} = 35 \times 12,5 \times 3.600 \text{ J / h} \\ &= \mathbf{1.575 \text{ kJ / h}} \end{aligned}$$

The heating power of the pupils per m³ of minimal ventilation is:

$$\begin{aligned} E_{\text{heating power} / \text{m}^3} &= E_{\text{heating power } 35 \text{ p}} \div V_{35 \text{ pupils}} \\ &= 1.575 \text{ kJ} / \text{h} \div 700 \text{ m}^3 / \text{h} \\ &= \mathbf{2.250 \text{ J} / \text{m}^3 \text{ or } 2,3 \text{ kJ} / \text{m}^3} \end{aligned}$$

The temperature *increase*, caused by the 35 pupils, is:

$$\begin{aligned} +\Delta t_{35 \text{ pupils}} &= E_{\text{heating power} / \text{m}^3} \div (\text{specific heat} \times \text{specific mass of air}) \\ &= (2.250 \text{ J} / \text{m}^3) \div (1.293 \text{ J} / ^\circ\text{C} / \text{m}^3) \\ &= \mathbf{1,74^\circ\text{C}.} \end{aligned}$$

The local thermal discomfort, caused by differences between the air temperature at the feet and the heads of the pupils cannot be large because the heads of the pupils are close to the cooling devices.

7.2 Relative Humidity

In Chapter 5, the influence on the relative humidity (RH), caused by both the pupils and the cooling devices was already calculated. In summary:

Table 9

Increase of the relative humidity (RH) on day 2 (33°C / 60%RH)

caused by:	influence	total
Pupils ¹	2% RH	(60% + 2% =) 62% RH
Cooling devices ¹	4% RH	(60% + 4% =) 64% RH
Pupils and cooling devices ¹	6% RH	(60% + 6% =) 66% RH

¹ Values from Chapter 5, not adjusted for the small temperature fluctuations of Paragraph 7.1.

ISO 7730 uses 60% RH for the general tables for summer days and 40% RH for the winter. An increase of the RH gives a decrease of the comfort temperature in the order of magnitude of 0,3°C per 10% of RH.

More specific, it distinguishes 3 categories for the built environment:

Category A, the most rigid, applies to people with special requirements with an allowable RH of 40% - 65%. The classroom only just surpasses the upper value. The comfort temperature would fall between 26°C - (0,3°C x 6% =) 1,8°C = 24,2°C and 26°C - (0,3°C x 1% =) 0,3°C = 25,7°C.

Category B is the standard category for new buildings for healthy people and an allowable RH of 30% - 70%. This is met by the circumstances in the classroom.

Category C is the most liberal and applies to older buildings and during renovations. The allowable RH again ranges from 40% to 70% RH.

Nota Bene: Day 1, the warm summer day in The Netherlands (27°C / 77% RH) does not comply with any of these categories and the days on which the perception tests were conducted (30°C / 30% RH) only barely comply.

7.3 Vapour pressure

The vapour pressure has a dependency on the air temperature and the RH (Lampinen, 2008). It follows (Engineering ToolBox, 2004):

- RH = $p_w \div p_{ws} \times 100\%$
- p_w = vapour partial pressure
- p_{ws} = saturation vapour partial pressure at actual dry bulb temperature, a look-up value (Engineering ToolBox, 2012)

The prevailing vapour pressure can hence be calculated from:

$$VP_{\text{prevailing}} = p_{ws} \times (RH \div 100\%)$$

The initial vapour pressure at 33,0°C and 60% RH

$$\begin{aligned} VP_{\text{initial}} &= p_{ws_{33,0^\circ\text{C}}} \times 0,6 = 5,0 \text{ kPa} \times 0,6 \\ &= \mathbf{3,0 \text{ kPa}} \end{aligned}$$

The air temperature decreases to 33,0°C - 2,08°C = 30,9°C attributable to the cooling devices. They increase the RH to 60% + 4% = 64% RH. The vapour pressure as a result of the influence of the cooling devices

$$\begin{aligned} VP_{\text{cooling devices}} &= p_{ws_{30,9^\circ\text{C}}} \times 0,64 = 4,5 \text{ kPa} \times 0,64 \\ &= \mathbf{2,9 \text{ kPa}} \end{aligned}$$

The air temperature increases to 33,0°C + 1,74°C = 34,7°C attributable to the pupils. They increase the RH to 60% + 2% = 62% RH. The vapour pressure as a result of the influence of the pupils

$$\begin{aligned} VP_{\text{pupils}} &= p_{ws_{34,7^\circ\text{C}}} \times 0,62 = 5,6 \text{ kPa} \times 0,62 \\ &= \mathbf{3,5 \text{ kPa}} \end{aligned}$$

The largest difference in vapour pressure (an academic worst case) would be at the highest temperature and the highest RH: 34,7°C and 66% RH

$$\begin{aligned} VP_{\text{worst case}} &= p_{ws_{34,7^\circ\text{C}}} \times 0,66 = 5,6 \text{ kPa} \times 0,66 \\ &= \mathbf{3,7 \text{ kPa}} \end{aligned}$$

7.4 Sound level

Worst case, it can be assumed, only 1 g of water is evaporated in 1 m³ of airflow in the cooling device. The water consumption at the desired maximum cooling power of 15 Watt per cooling device follows again

$$\begin{aligned} m_{15 \text{ Watt}} &= (\text{cooling power} \div \text{enthalpy of vaporization}) \times 3.600 \text{ s} \\ &= (15 \text{ Watt (J / s)} \div 2.260 \text{ (J / g)}) \times 3.600 \text{ s} \\ &= \mathbf{24 \text{ g / h}} \end{aligned}$$

The required airflow

$$\begin{aligned} V_{\text{required}} &= 1 \text{ g / m}^3 \times 24 \text{ g / h} \\ &= \mathbf{24 \text{ m}^3 \text{ / h}} \end{aligned}$$

A modern Akasa AK-FN058 fan of 120 x 120 x 25 mm³ can deliver 57 CFM or 97 m³ / h at 1.300 RPM. The relation between airflow and RPM is linear (Akasa, 2017) so the fan will deliver 24 m³ / h at ((24 m³ / 97 m³) x 1.300 RPM =) ~ 320 RPM. Assumed is a required 400 RPM. The sound production of this fan has the following relation:

Table 10

(predicted) Sound level of the Akasa AK-FN058 fan

sound level	RPM	relation
6,9 dB (A)	600	(6,9 ÷ 600 =) 0,0115
16,05 dB (A)	1.400	(16,05 ÷ 1.400 =) 0,0115
4,6 dB (A) =	400 (calculated / assumed)	x (assumed) 0,0115

4,6 dB (A) and 6,9 dB (A) are barely audible (IAC Acoustics, 2019). According to the earlier source (Ego, 2014), 4,6 - 6,9 dB (A) fall in the *Very Faint* range:

0 - 30 dB (A), Very Faint. Most human adults cannot hear sounds below 0 decibels. Most sound in this range is almost inaudible. Sounds that create decibel levels between 0 and 30 include whispers and the ticking of a watch.

7.5 Average radiation temperature

This is, of course, the main thing for the cooling device, yet impossible to capture in a generic calculation: The average radiation temperature is the mean value of all surface temperatures: Ceiling, floor, walls, windows, heaters and furnishings. Of these, there are no averages.

According to ISO 7730:2005, the radiation temperature should preferably be the same as the air temperature to get the highest level of thermal comfort, just as assumed in the calculations for the heat loss break down of a human, summarized in Table 1. As contrasting examples: Sitting close to a single pane window on a grey, cold winter day makes a human cool down, regardless of the ambient air temperature, because the single pane window allows the human to lose his radiation heat easily, whereas a human, exposed to direct sunlight on winter sports holidays, heats up, notwithstanding the possible sub-zero ambient air temperature. The radiation temperature should also have a good symmetry to be comfortable. Coolness from one side is more manifest. Radiant temperature asymmetry causes local thermal discomfort. Especially a warm ceiling is perceived as unpleasant from 2°C difference onwards. To a lesser degree, respectively a cool wall (from 7°C onwards), a cool ceiling (from 8°C onwards) and a warm wall from 8°C onwards, but only little dissatisfying (ISO 7730:2005). In accordance with that, inside the built environment, a difference of 5°C between radiation temperature and air temperature is considered undetectable (Van der Ree, 2009).

As the test of the lab model in Chapter 6 showed, the cold wall of the heat exchanger almost reached the dew point, it may well be, that the new cooling device does not stay undetectable which may imply, it is uncomfortable. Table 6 already showed the dew point and cooling power per m² under different conditions and Table 7 the cooling power per 1/3 m² of cooling device and the water consumption. In Table 11 a recapitulation.

Table 11

The difference in radiation and air temperature under different conditions

ambient circumstances	dew point	temperature difference
27°C / 77% RH ¹ / 9 W ²	22,5°C ³	(27°C - 22,5°C =) 4,5°C
33°C / 60% RH ¹ / 19 W ²	24,0°C ³	(33°C - 24,0°C =) 9,0°C
30°C / 30% RH ¹ / 37 W ²	10,5°C ³	(30°C - 10,5°C =) 19,5°C

¹ Ambient circumstances from Table 5; ² cooling power from Table 7; ³ dew point from Table 6.

If the cooling device is indeed as efficient as the lab model, only the first line of Table 11 complies with the 5°C rule. Moreover, according to Figure 13: Heat loss of the human, only little cooling power is needed at an ambient temperature of 27°C. On day 2 (33°C), the cooling power of the cooling device is already more than the 15 Watt needed at most.

The second two temperature differences imply, that the cooling power of the cooling device should be tempered which will be beneficial to all aspects of thermal comfort, influenced by the cooling device.

The easiest and most controllable way is to limit the airflow with proportional

benefits to all aspects of thermal comfort, influenced by the cooling device: The evaporation will decrease, hence the water consumption will decrease and hence the influence on the RH will decrease; The sound level and the energy consumption will decrease even further.

To get to the cooling power down to the desired maximum of 15 Watt, the airflow reduction factor for day 3 (30°C / 30% RH, dew point 19,5°C)

$$\begin{aligned} f_{\text{reduction}} &= (\text{desired maximum power}) / (\text{cooling power on day 3}) \\ &= 15 \text{ Watt} / 37 \text{ Watt} \\ &= \mathbf{0,41} \end{aligned}$$

As the lab model did not reach the exact dew point, a bit more air will be needed to reach enough cooling power on days 1 and 2 and therefore a reduction factor $f_{\text{reduction used}}$ of 0,5 will be used next. The sound output of the fan will then also halve.

The RH at which the desired maximum of 15 Watt cooling power per device (= 30 Watt at full speed = $3 \times 30 = 90 \text{ Watt} / \text{m}^2$) on a day of 30°C is reached, *Situation X*, can be calculated according to page 37 ff. from the Stefan-Boltzmann law: $E = \sigma T^4$:

Situation X: Air temperature 30°C / 303,15K, cooling power 90 Watt

$$\begin{aligned} E_{\text{cooling power s. X}} &= 90 \text{ W} / \text{m}^2 = E_{303,15\text{K}} - E_{\text{situation X}} = 479 - 90 \text{ W} / \text{m}^2 \\ E_{\text{cooling power s. X}} &= \mathbf{389 \text{ W} / \text{m}^2} \\ E_{\text{cooling power s. X}} &= \sigma T^4 = 5,670 \times 10^{-8} \times (T_{\text{situation X}})^4 \\ (T_{\text{situation X}})^4 &= E_{\text{situation X}} / \sigma = 389 \div 5,670 \times 10^{-8} = 6.860.670.194 \\ T_{\text{situation X}} &= \mathbf{287,8 \text{ K}} \text{ or } 14,65^\circ\text{C} \end{aligned}$$

The corresponding relative humidity at 30°C (the magenta line in Figure 3):

$$\text{RH}_{\text{situation X}} = \mathbf{40\%}$$

An overview is given in Table 12.

Table 12

Cooling power of a cooling device of 1/3 m² with half the airflow

ambient circumstances	earlier cooling power	final cooling power
27°C / 77% RH ¹	9 Watt ²	(0,5 x 9 W =) 4,5 Watt
33°C / 60% RH ¹	19 Watt ²	(0,5 x 19 W =) 9,5 Watt
30°C / 40% RH (<i>Situation X</i>)	90 Watt	(1/6 x 90 W =) 15,0 Watt
30°C / 30% RH ¹	37 Watt ²	(0,5 x 37 W =) 18,5 Watt

¹ Ambient circumstances from Table 5 on page 27; ² Cooling power from Table 7 on page 38.

These values are- grosso modo- in line with the desired 5 - 15Watt range.

From the final cooling power (x 3 to get the power per m²), the temperature of the wall of the device, facing the human, can again be calculated from the Stefan-Boltzmann law and the values from Chapter 5, summarized in Table 13:

Situation 1: Air temperature 27°C / 300,15K, dew point 22,5°C / 295,65K, cooling power s.1.1 (3 x 4,5 Watt =) 13,5 Watt / m².

$$\begin{aligned}
 E_{\text{cooling power s. 1.1}} &= E_{300,15K} - E_{\text{final 1}} \\
 13,5 \text{ Watt / m}^2 &= 460 \text{ W / m}^2 - E_{\text{final 1}} \\
 E_{\text{final 1}} &= 460 \text{ W / m}^2 - 13,5 \text{ Watt / m}^2 \\
 &= 446,5 \text{ W / m}^2 \\
 (T_{\text{final s.1.1}})^4 &= 446,5 \div \sigma = 446,5 \div 5,670 \times 10^{-8} = 7.874.635.798 \\
 T_{\text{final s.1.1}} &= \mathbf{297,89K} \text{ or } 24,74^\circ\text{C}
 \end{aligned}$$

Situation 2: Air temperature 33°C / 306,15K, dew point 24,0°C / 297,15K, cooling power s.2.1 (3 x 9,5 Watt =) 28,5 Watt / m²

$$\begin{aligned}
 E_{\text{cooling power s. 2.1}} &= E_{306,15K} - E_{\text{final 2}} \\
 E_{\text{final 2}} &= 498 \text{ W / m}^2 - 28,5 \text{ Watt / m}^2 = 469,5 \text{ Watt / m}^2 \\
 (T_{\text{final s.2.1}})^4 &= 469,5 \div \sigma = 469,5 \div 5,670 \times 10^{-8} = 8.280.202.037 \\
 T_{\text{final s.2.1}} &= \mathbf{301,65K} \text{ or } 28,50^\circ\text{C}
 \end{aligned}$$

Situation X: Air temperature 30°C / 303,15K, dew point 14,65°C / 297,15K, cooling power situation X (3 x 15,0 Watt =) 45,0 Watt / m²

$$\begin{aligned}
 E_{\text{cooling power s. X}} &= E_{303,15K} - E_{\text{final X}} \\
 E_{\text{final 2}} &= 460 \text{ W / m}^2 - 45,0 \text{ Watt / m}^2 = 415,0 \text{ Watt / m}^2 \\
 (T_{\text{final s.2.1}})^4 &= 415,0 \div \sigma = 415,0 \div 5,670 \times 10^{-8} = 7.319.223.986 \\
 T_{\text{final s.2.1}} &= \mathbf{292,49} \text{ or } 19,34^\circ\text{C}
 \end{aligned}$$

Situation 3: Air temperature 30°C / 303,15K, dew point 10,5°C / 283,65K, cooling power s.3.1 (3 x 18,5 Watt =) 55,5 Watt / m²

$$\begin{aligned}
 E_{\text{cooling power s.3.1}} &= E_{303,15K} - E_{\text{final 3}} \\
 E_{\text{final 3}} &= 460 \text{ W / m}^2 - 55,5 \text{ Watt / m}^2 = 405 \text{ Watt / m}^2 \\
 (T_{\text{final s.3.1}})^4 &= 405 \div \sigma = 405 \div 5,670 \times 10^{-8} = 7.142.857.143 \\
 T_{\text{final s.3.1}} &= \mathbf{290,71} \text{ or } 17,56^\circ\text{C}
 \end{aligned}$$

Day 1 and day 2 comply. On day X, day 3 and other days with a very low RH, the radiant temperature of the cooling device may get lower than the desired 5°C under the ambient air temperature.

Table 13*Data of a cooling device of 1/3 m² with half the airflow*

ambient circumstances	final cooling power	temperature difference
27°C / 77% RH	4,5 Watt	(27°C - 24,7°C =) 2,3°C
33°C / 60% RH	9,5 Watt	(33°C - 28,5°C =) 4,5°C
30°C / 40% RH	15,0 Watt	(30°C - 19,3°C =) 10,7°C
30°C / 30% RH	18,5 Watt	(30°C - 17,6°C =) 12,4°C

The difference on day X and day 3 may even cause radiant temperature asymmetry and hence cause local thermal discomfort. Still, this stays limited to only 2% of the people (ISO 7730:2005).

7.6 Relative speed of the airflow (draught, for example)

In the tiny classroom of 42 m², the needed ventilation airflow was 700 m³. Assume, that all ventilation air flows through one open door of 1 x 2,10 m². Hence 700 m³ passes through 2,1 m² in one hour.

The average local air speed at the door opening, caused by the ventilation

$$\begin{aligned}
 V_{\text{air ventilation local}} &= 700 \text{ m}^3 / \text{h} \div 2,1 \text{ m}^2 \\
 &= 333 \text{ m} / \text{h} \text{ or } 333 \text{ m} / \text{h} \div 3.600 \text{ s} \\
 &= \mathbf{0,0925 \text{ m} / \text{s}}
 \end{aligned}$$

The 35 cooling devices, worst case- still with the non-tempered fan speed- and not a part of the ventilation of the classroom, make an extra circulation of 35 x 24 m³ (Paragraph 7.4) for a total of 840 m³.

The average local air speed at the door opening, caused by the devices, is:

$$\begin{aligned}
 V_{\text{air devices local}} &= 840 \text{ m}^3 / \text{h} \div 2,1 \text{ m}^2 \\
 &= 400 \text{ m} / \text{h} \text{ or } 400 \text{ m} / \text{h} \div 3.600 \text{ s} \\
 &= \mathbf{0,1111 \text{ m} / \text{s}}
 \end{aligned}$$

According to ISO 7730:2005, higher air speeds allow higher temperatures and higher relative humidity, due to the cooling effect that air movement has on an individual. 0,1 m / s is *mostly undetectable* for a maximum allowable elevated airspeed of 1,5 m / s (Hoyt, Schiavon, Piccioli, Moon, & Steinfeld, 2013). The sum of the two air speeds (0,2036 m / s) meets the requirements.

In Table 14 alongside the summary of Chapter 7.

Table 14*Influence of the cooling device on the 6 relevant aspects of thermal comfort*

aspect	source	influence
air temperature (devices)	Paragraph 7.1	-2,08°C
air temperature (pupils)	Paragraph 7.1	+1,74°C +
Air temperature (overall)		-0,34°C
Air temperature (local)	Paragraph 7.1	negligible discomfort
Δ RH (devices)	Table 9	+4% RH
Δ RH (pupils)	Table 9	+2% RH
Δ RH (both)	Table 9	10% increase or +6% RH
Relative humidity (overall)	Paragraph 7.2	(near perfect) acceptable
vapour pressure (initial)	Paragraph 7.3	3,0 kPa
vapour pressure (devices)	Paragraph 7.3	2,9 kPa
vapour pressure (pupils)	Paragraph 7.3	3,5 kPa
vapour pressure (worst)	Paragraph 7.3	3,7 kPa
Vapour pressure (overall)	ISO 7730:2005	compliant
sound level fan	Table 10	(near inaudible) ~ 5 dB (A)
Sound level fan (@ 50%)	Paragraph 7.5	(near inaudible) ~ 2,5 dB (A)
$\Delta t_{\max.}$ device, day 1	Table 11	-4,5°C
$\Delta t_{\max.}$ device, day 2	Table 11	-9,0°C
$\Delta t_{\max.}$ device, day 3	Table 11	-19,5°C
Δt device @ 50%, day 1	Table 13	-2,3°C
Δt device @ 50%, day 2	Table 13	-4,5°C
Δt device @ 50%, day 3	Table 13	-10,7°C
Radiation temperature	Paragraph 7.5	day 1 & 2: compliant
Radiant asymmetry	ISO 7730:2005	day 3: 2% dissatisfied
air speed (ventilation)	Paragraph 7.6	0,0925 m / s
air speed (devices)	Paragraph 7.6	0,1111 m / s +
air speed (total)		0,2036 m / s
Relative airflow speed	(Hoyt et Al, 2013)	(near) mostly undetectable

(empty)

8: The first real designs

According to the test of the lab model in Chapter 6, Table 13 and the rest of Chapter 7, a cooling device, laid out as $1/3 \text{ m}^2$ of single sheet heat exchanger of an indirect evaporative dew point cooler should suffice, as long as the radiant temperature has a good symmetry and a solution is found for the high thermal conductivity of the wall of the heat exchanger if or when it comes in contact with the skin of the individual who is to be cooled down.

According to page 18 in Chapter 1, the face and ears have the highest density of thermoreceptors, the face perceives thermal changes in the environment the strongest, and, although the facial skin area is only 4 to 5% of the entire body surface, under radiant heating, the face will cause 20% of the perspiration drive of the body, all of which makes it the natural choice to focus the design on a table top cooler, putting it in 'direct sight' of the face of its user.

This makes the avoidance of high thermal conductivity of the upper area of the cooled down wall inevitable, as the arms of the user will often rest on the tabletop and therefore now rest on the top of the cooling device. This paradoxically implies, that the cooled down wall should be thermally conductive through the thickness of the wall to transfer the heat, extracted from the wet side, and at the same time thermally insulating on the outer surface itself to avoid conductively cooling down of the skin of its user.

Water distribution in the lab model was absent: The tea towel in it was wetted with tap water and wetted again after it got dry. To keep the cooling device simple, it would be best to make the water distribution (semi-)passive, that is: Without a pump or nozzles. According to Table 8 in Chapter 5, the water consumption should be around $14 - 59 \text{ g / h}$, calculated for the higher speed of the airflow. This will then only be about $7 - 30 \text{ g / h}$ at half the fan speed.
A glass of water a day.

Day 2 requires $0,5 \times 30 \text{ g / h}$ or $(0,5 \times 30 \text{ g / h} \times 8 \text{ h} \Rightarrow) 120 \text{ g}$ per working day, taken as a starting point for the volume of the first water storage container.

The Akasa AK-FN058 fan of $120 \times 120 \times 25 \text{ mm}^3$, used in Paragraph 7.4 to estimate the sound level is suitable as it is near inaudible silent and its speed can be regulated.

The top layer is thought in a faux leather, a thin layer of plastic (with low conductivity), backed by a woven gauzelike absorbent fabric, now used for clothes. The top layer is supported by the upper side of the airflow chamber. The airflow chamber in its turn must be highly perforated to get the airflow in contact with the woven fabric.

The fabric must also be in contact with the (preferably (semi-)passive) water supply to have the absorbent characteristic of the fabric spread the water over the entire underside of the surface of the top layer.

The first design is an almost verbatim translation. See Figures 15 and 16 alongside. It consists of:

- 01 A small, 120 cc water reservoir that may be detached and provides (semi-)passively a little pressure to the water in the water distribution system;
- 02 A connection for the detachable reservoir;
- 03 The very thin, insulating layer that 'absorbs' the radiant heat from its user, thin enough to not affect the cooling power much;
- 04 The woven backing layer to spread the water via absorption;
- 05 The chamber for the airflow, made of twin wall polycarbonate sheet with rectangular holes in the top wall of it to get the wetted backing fabric in contact with the airflow and still able to support the faux leather;
- 06 Channels to feed the water from the reservoir to the absorbing woven fabric;
- 07 A now smaller Akasa AK-181BK-S Ø 80 mm fan to be able to reduce the airflow even more when needed and running from a USB-port;
- 08 A plenum to duct the airflow evenly into the chamber.

The area of the design should be around $\frac{1}{3} \text{ m}^2$ or $0,33 \text{ m}^2$. In The Netherlands, the smallest desks, used in elementary school are $50 \times 70 \text{ cm}^2$, or $0,35 \text{ m}^2$ (EromesMarko, 2016), close to $\frac{1}{3} \text{ m}^2$ and a practical reference point.

The layout is left-to-right symmetrical and focuses on the face when put on a tabletop. The fan-and-plenum is under the tabletop or inside the compartment of the primary school desk.

Figure 15. First design of the cooling device.

Figure16. Side view of the first design of the cooling device.

Pupils now cannot lean against the edge of the desk because of the plenum curving around the edge of the tabletop to the fan, located under the tabletop or inside the desk's compartment. A flat layout with multiple small fans replacing both the one larger fan and the plenum would make the cooling device more practical and multi-purpose.

The plenum and fans are integrated in the volume of the chamber of the cooling device in the second design: The prototype is on the next page.

Instead of the one larger fan, the second design has 6 smaller fans (Sunon GM0503PEV2-8), rated $6,29 \text{ m}^3 / \text{h}$ at 5VDC / 80mA and 24 dB (A), making a total airflow of $6 \times 6,29 \text{ m}^3 / \text{h} = 37,74 \text{ m}^3 / \text{h}$ (Sunon, 2013). To temper the airflow, the fans are wired in series per pair, which should-be similar to the Akasa fan- halve the airflow to a rated $18,9 \text{ m}^3 / \text{h}$ at the intake and can still be powered from a USB-port. The sound level per fan will fall to $(0,5 \times 24 =) 12 \text{ dB (A)}$, making $(12 \text{ dB (A)} + 10 \log 6 =) \sim 20 \text{ dB (A)}$ for all six. The fans (and water reservoir) are placed at the far side of the cooling device to avoid contact with its user. The faux leather top layer combines the very thin insulating layer (03) and the capillary fabric (04) again.

Figure 17. The chamber of the second design under construction.

Figure 18. Prototype of the second design, connected to a USB-port.

The prototype of the cooling device was put to the test to assess its features.

8.1 The airflow

In Paragraph 7.4, a theoretical airflow of $24 \text{ m}^3 / \text{h}$ was calculated and in Paragraph 7.5, an airflow reduction factor of $0,41 - 0,50$ was introduced. This implies a desired airflow of $24 \text{ m}^3 / \text{h} \times 0,41 - 0,50 = 9,84 - 12 \text{ m}^3 / \text{h}$. The 6 small fans, wired in series, have a theoretical combined airflow of $18,9 \text{ m}^3 / \text{h}$. The airflow at the exhaust was measured by filming the speed of tobacco smoke, flown through the fans of the prototype for an exhaust speed of $0,3 - 0,4 \text{ m} / \text{s}$, which amounts to $\sim 10 \text{ m}^3 / \text{h}$, in the middle of the calculated desired airflow despite the small channels in the twin wall polycarbonate sheet ($8 \times 8 \text{ mm}^2$), that apparently cause a loss of airflow of circa 50%. If drag is reduced, there is more latitude to adjust the airflow and hence, the cooling power. Still, the height of the tabletop cooling device should be kept as low as possible (currently 11 mm at the lower end).

Figure 19. Still from the film, recording the air speed at the exhaust.

Despite the fact, that the fans are placed at the far end of the cooling device, touching the fans seems inevitable. This will shorten the life span.

The contact temperature measurements did not render clear readings. In the next, better prototype, these should be repeated with a different tool.

The air exhaust is now aimed at the human. Especially when sweating, this proved to be cold and very unpleasant.

The prototype of the cooling device is slightly tilted toward its user, caused by the plenum for the airflow of the fans at the far end of the device. It would probably be better to make the surface of the cooling device plane-parallel with the tabletop.

8.2 Water distribution

The prototype of the cooling device tends to leak small amounts of water from the exhaust, now aimed at the human. This amplifies the sensation of discomfort, caused by the airflow itself. The leakage may be caused by the strong absorbent action in the woven fabric backing or by the elevated water level in the reservoir.

8.3 The top layer

The faux leather gets indented at the square holes in the top layer of the chamber within seconds of use. It looks prone to perforation and gives the first prototype a botched look. The surface structure of the twin wall polycarbonate sheet itself is also clearly visible, even through an extra layer of two-sided adhesive tape at the fans, making the cooling device look even more botched. Although it seems feasible to cut the holes in the polycarbonate sheet via an industrial process, the chamber of the cooling device cannot be made in one simple process.

Figure 20. Close-up of the fans, the water reservoir and the indentations.

8.4 Miscellaneous

The fans, placed in the open, are not everyone's taste as is the water reservoir. It looks unprofessional and in my eyes ugly, as does the protruding water reservoir. After shutting down, the woven fabric stays damp for a long time, days on end. That may cause health issues, addressed in the next chapter.

8.5 Pro's

The size is very convenient when, for example, used with a laptop.

By subjective evaluation: People, seated at the cooler do cool down because they stopped sweating actively.

9: Health issues

The woven backing of the faux leather doesn't get dry quickly. It took up to several days. The dead-ended water distribution tubes also did not dry entirely. The tubes can catch a little daylight and get greenish like the level indicator in a filter type coffee maker, probably caused by the growth of algae. The leakage from the woven gauze backing, described in Paragraph 8.2 may theoretically cause aerosols, very tiny water drops (like for example the 'steam' from a shower) that could be entrained in the forced airflow. These conditions may promote growth of microorganisms in the system, posing a potential health risk if or when aerosols are produced.

Water aerosols, suspended in air can spread diseases like a sneeze can spread a cold. Of course, the cooling device has no direct influence on diseases, spread by coughing but could spread diseases, caused by certain microorganisms that may be present in tap water. Drinking water in the Netherlands complies with high water quality criteria defined in national legislation (Drinkwaterbesluit; Staatsblad 2011 293:1-90), which complies with EU-legislation. Microbiological water quality criteria include the absence of bacteria of fecal origin (*Escherichia coli* and *Enterococci*) in 100 ml of water. Additional criteria are absence of *coliforms* and *Clostridium perfringens* in 100 ml, less than 1000 colony forming units (CFU) of *Aeromonas* in 1 litre and a heterotrophic plate count of < 100 CFU/ml. Furthermore, the colony count of *Legionella* must be less than 100 CFU/litre. Certain bacteria of the genus *Legionella*, in particular *Legionella pneumophila* can cause legionellosis or Legionnaires' disease and spreads via aerosols. Infection with *L. pneumophila* is often lethal. Legionnaires' disease may be spread via the cooling device and its presence should absolutely be avoided.

Pneumophila, the etiologic agent of Legionellosis, is found in low concentrations in tap water and can grow in water installations (Fields et al, 2002). *L. pneumophila* is harmless when swallowed yet very infectious when inhaled in aerosols that can reach the deepest capillaries in the lungs.

The organism proliferates in amoebae (Fields et al, 2002), which are mainly found in biofilms on surfaces exposed to water (Kuiper et al. 2004), in particular at temperatures between 25°C and 50°C (Regeling Legionellapreventie, 2011).

Biofilms are composed of microorganisms that strongly adhere to a surface and are capsulated in polysaccharide material (Donlan, 2002). Factors promoting biofilm formation include the presence of nutrients in the water, in particular biodegradable organic compounds and the nature of the water-exposed materials. Certain synthetic materials release biodegradable constituents that promote biofilm formation (Hamsch et al. 2014).

Consequently, prevention of biofilms requires the use of water with a low nutrient concentration and materials that do not promote biofilm formation. Furthermore, maintaining a low temperature and prevention of stagnation also limits biofilm formation and growth of pathogens.

Figure 21. Different stages of proliferation of *L. pneumophila*: From a single, free red dot in A, to the yellow dots in B, now multiplying inside the green amoebae, and taking up an entire amoeba in C, after which the amoeba lyses, giving a plethora of *L. pneumophila* (Kuiper et al, 2004).

To prevent growth of *Legionella* and other undesirable microorganisms in the cooling device, measures are needed to eliminate potential risk factors:

- 1 Only water that complies with the quality criteria defined in drinking water legislation should be used in the cooling device;
As stated above, drinking water is very clean¹.

- 2 The critical water temperature is between 25°C - 50°C.
Water below 20°C shows no risk (fresh tap water) and between 20°C - 25°C very little risk. The water in the device will however reach the ambient temperature, i.e. within the range of 25°C - 50°C. In this temperature-interval, 2 days is the maximum time of residence².
- 3 Stagnant water is to be avoided.
Dead ended tubing will have stagnant water. Any fabric that does not dry out quickly has a sort of stagnant water in them. In stagnant water, biofilm could grow and then the amoebae, etcetera.
- 4 Any form of long residence or hot spots are to be avoided.
Any part where the water can reach a temperature of over 25°C is considered a hot spot³.
- 5 Aerosol forming is to be avoided.
*As already stated before, *L. pneumophila* is very infectious when inhaled in aerosols that can reach the deepest capillaries in the lungs.*
- 6 All surfaces and used materials should be of non-growth-promoting materials.
*Some materials show less sediments, oxidation and surface growth of biofilm on which the protozoa in which the *L. pneumophila* will prosper. For example glass, non-corrosive metals like stainless steel 316 and PVC-C⁴.*

¹ Drinkwaterbesluit; Staatsblad 2011 293:1-90; ² Regeling legionellapreventie in drinkwater en warm tapwater, Bijlage 2, Paragraph 5.2; ³ Regeling legionellapreventie in drinkwater en warm tapwater, Bijlage 2, Paragraph 1; ⁴ Van der Kooij, Veenendaal & Scheffer, 2005.

The new cooling device is intended to use tap water. Still, the first designs of the cooling device and their operating conditions *do not* comply with the preventive measures 2 - 6 mentioned above:

- @2 The ambient temperature in the occupied space will often be above 25°C and the water in the reservoir will easily warm up to that value, too, as the specific heat of water is only 4,18 J / g / K (BINAS, 1998).
- @3 The tubing for the water distribution is all dead-ended with stagnant water in which green, slimy deposits form. The tubing hardly dries out at all. The woven backing fabric takes several days to completely dry out.
- @4 The tiny water reservoir tends to retain a little water, making it reside longer. The chamber of the cooling device will eventually reach the ambient temperature and must therefore be considered a hot spot.
- @5 The woven backing drips a little bit. This is not an immediate source of aerosols but it is similar to sprinkling, which is as well to be avoided, also because there is an- albeit slow- forced airflow.

- @6 The water distributing tubes are made of plasticized polyvinyl chloride (PVC-P), a growth-promoting material, as described in @ 3. The fabric does not remain clean either.

The following preventive measures should be taken in the final design to eliminate the risk factors mentioned above:

- 1 The cooling device must dry out completely at least once a day. This will also eliminate the dangers of the hot spot the cooling device inevitable is.
- 2 The water-spreading layer in the device must be leak-free, to reduce the risk of aerosol forming to the absolute minimum, and besides that, if the risk factors 2 - 4 are eliminated, the risk of growth of *L. pneumophila* is already minimized.

If the water-spreading layer is leak free, it could still be considered as a water surface. Aerosol forming from water surfaces is observed at air speeds over 3 - 4 m / s (Ramachandran, 2018). The measured air speed at the exhaust of the device is 0,3 - 0,4 m / s, which was corresponding with an airflow of circa 50% of the theoretical output of the fans (Paragraph 8.1).

This implies an airspeed of 0,6 - 0,8 m / s at the inlet of the prototype, which makes the forming of aerosols with the chosen fans and calculated airflow hypothetical, anyway.

- 3 All materials in contact with water, used for the final design must be non-growth-promoting.

The above and the demands, stemming from Chapter 8 necessitate an entirely new design layout in all different materials yet still based on the same cooling principle.

10: The final design

The final design must meet the demands from Chapter 8 and comply with the risk factors of Chapter 9.

It is a long list:

From Chapter 8:

- The airflow must be directed away from the human.
- Tilting the cooling device is better avoided.
- The water reservoir should be non-obstructive.
- The fans should be protected from contact.
- The entire cooling device should be kept shallow.
- The cooling device should preferably be entirely flat.
- The top layer of the cooling device needs to be more rigid.
- The water distribution must be leak free.
- The right water spreading fabric should avoid leakage.
- The air channels should preferably be wider to reduce drag.
- The cooling device should look (and keep) clean and professional.
- The dimensions of the surface area can be maintained.

From Chapter 9:

- The device must dry out completely on a daily basis. This means,
- The water spreading material must dry out completely, too;
- Dead end tubing and stagnant water must be avoided, as should long water residence and hot spots;
- Aerosol forming must be avoided;
- All materials and surface finishes in contact with water must be non-growth-promoting.

The performance of the cooling device- under average summer day conditions- is well contained within the margins, dictated by the ISO 7730-standard and physiological demands. It does not need any power control device because it is self-regulating. Only on days with very low RH, it will over-perform slightly.

This chapter will motivate the final design and its materialisation from the working principle of the water distribution, via the selection of the used materials to the colour of the top layer.

10.1 Water distribution

Chapter 9 showed, that aerosol forming from water surfaces is observed at air speeds over 3 - 4 m / s and Paragraph 8.1 showed, that the measured air speed at the exhaust of the device is 0,3 - 0,4 m / s and will be twice that directly after leaving the fans. The forming of aerosols inside the device is therefore quite theoretical.

If the water distribution would depend on capillary action only, leakage can be avoided by choosing the right water-spreading layer. By creating a water reservoir below the top surface of the device, the (tiny) pressure, generated by the elevated water reservoir is avoided.

If the water spreading depends on capillary action only (without the absorbing 'suction' of the backing fabric), a drip-free layer may be created.

The interior being drip-free and the air speed at the low level it is, will assure, that the risk on aerosol forming is almost imaginary.

The chosen water-spreading layer must dry out completely after use.

In many existing evaporation based cooling systems, *hygroscopic* materials are used to retain the water (Air@Work, 2015, US Patent 2003145609, etc.).

Hygroscopic means *absorbing water from the air* (Cambridge Dictionary, n.d.) or *readily taking up and retaining moisture* (Webster, 2002). These materials are unfit because they intrinsically will not get dry easily or completely.

As mentioned at [6] on page 63, some materials are non-growth-promoting, i.e. stainless steel, glass and PVC-C. This indicates, that a stainless steel fabric or glass fabric, used as a capillary water-distributing layer could be a clean solution. In addition, stainless steel and glass itself cannot absorb water and could therefore get dry completely.

The water reservoir must also get dry entirely, using again non-growth-promoting materials.

As the water, used in the cooling device, should be as clean as (and will mostly be) tap water, it will likely be below 20°C (with 25°C as the very maximum at the tap, according to the Dutch concept Drinkwaterbesluit of 2018). Still, water will warm up easily when in contact with the top layer of the device. The specific heat of water is only 4,18 J / g / K (BINAS, 1998), much less than the enthalpy of vaporization (2.260 J / g) and will hence quickly heat up to the temperature of the chamber of the device (which will be close to the ambient temperature) or of the top layer of the cooling device.

This is close to the worst-case temperatures for the growth of *L. pneumophila*.

If the water reservoir gets completely depleted regularly, it will thus get dry and thus be non-growth-promoting. The 120 cc from Chapter 8 seems a good starting point as it means circa one replenishment per working day in the summer or one more on a day with very low relative humidity.

10.2 The capillary layer

A specific glass fibre mat, 300 grams / m² powder bound chopped strand mat (CSM), performed the capillary action as desired and dried up completely after the water supply was depleted.

To test whether the capillary action of glass fibre mats is enough to draw water from underneath the top layer of the cooling device, a simple laboratory test was set up. Various glass fibre samples were clamped to the bottom side of an elevated horizontal pane of glass and guided down into a water reservoir on a letter scale. See Figure 22 on page 68 and Figure 23 on page 69.

Ideally, the glass fibre should suck itself- via capillary action- to the bottom of the pane of glass and release itself after drying out, allowing the windowpane to dry out, too.

Several glass fibre *fabrics* (with warp and woof) were tested because of their mechanical integrity. These did not show any capillary action whatsoever. Subsequently, several thin and dense glass fibre tissues with chopped and randomly spread strands of glass, CSM's, were tested. These, again, did not show any capillary action at all.

A specific glass fibre for building and repairing glass fibre reinforced polyester car bodies and boats was tested last. It turned out, that this powder bond Chopped Strand Mat (CSM), a thick layer glass fibre tissue, *hakselmat* of 300 g / m² from Wilsor BV, Biddinghuizen, The Netherlands, performed as desired. It has a less dense structure, a larger thickness and the highest mass per square metre of the tested samples.

Table 15 gives an overview of the performance of the tested glass fibre fabrics and tissues.

Table 15

Capillary action of glass fibre fabrics and tissues

supplier and number	mass	description	capillary action
Conrad 886588 ¹	49 g / m ²	Very thin glass fabric	0%
Conrad 886587 ¹	220 g / m ²	Medium glass fabric	0%
Conrad 886590 ¹	163 g / m ²	Silky smooth glass fabric	0%
Wilsor ²	30 g / m ²	Thin glass fleece	0%
Conrad 886589 ¹	80 g / m ²	Thin glass fabric	0%
Conrad 886614 ¹	163 g / m ²	Medium glass fibre tissue	0%
Conrad 886613 ¹	80 g / m ²	Very thin glass fibre tissue	0%
Wilsor ²	100 g / m ²	Thin glass fibre tissue	0%
Wilsor ²	200 g / m ²	Medium glass fibre tissue	0%
Wilsor ²	300 g / m ²	Thick layer CSM (<i>hakselmat</i>)	100%

¹ Supplied by Conrad Electronic Benelux BV; ² Supplied by Wilsor BV.

Figure 22. Testing the capillary water flow of glass *fabric*.

Figure 22 shows the water supply on the digital scale on the left. The glass fabric should stick to the bottom of the glass. The glass fibre *fabrics* showed no capillary action whatsoever, even after wetting the fabric beforehand (shown).

Figure 23 alongside clearly shows how far the water travelled when the picture was taken (circa 15 centimetres). It is the darker portion, sucking itself to the glass, the rest of the ribbon (the bright white part on the right) still dry. The ribbon wasn't wetted beforehand and the water travelled up from itself from the reservoir. The capillary action stopped when the CSM seemed saturated and without the occurrence of any leakage whatsoever. After removing the water reservoir, both the window and the CSM dried out completely within half an hour, the CSM releasing itself from the glass. Because this specific CSM adheres to the top layer (the glass pane in Figures 22 and 23) and releases itself too, the top layer may be chosen freely as long as it mimics the even flatness of the glass windowpane and complies to condition [4]- being non-growth-promoting- of Chapter 9.

Figure 23. The capillary water flow through the Wilsor thick layer CSM of Table 15: Hakselmat of 300 g / m².

10.3 Ventilation

As it will be advantageous to ventilate the cooling device until entirely dry, the cooling device should not be turned off before *being* indeed completely dry. Paragraph 7.5 showed, that the energy consumption is around 2 Watt. If the device is not entirely dry at the end of its day of use, the device can be left powered on, overnight. This won't cost much energy and it will force the device to dry entirely.

The noise level is low (Paragraph 7.4: 2,5 - 5 dB (A) for the larger Akasa fan or 20 dB (A) for the 6 small fans from Chapter 8), all in the *Very Faint* range.

A small price for cleanliness and security.

To avoid the air stream being aimed at the user of the cooling device, the airflow could be from left to right instead of front to back (the first design with the protruding, obstructive large fan-and-plenum under the tabletop) or back to front (the second design with the 6 little fans).

10.4 The top layer

No material will conduct heat perfectly at room temperatures. There is some gradient of temperature that differs from material to material. Some materials insulate heat well and others conduct it well. This is indicated by the thermal conductivity.

Fourier's law, the law of heat conduction, states, that the speed of heat transfer through a material is proportional to the negative temperature gradient (Van Herwijnen, Leijendeckers, De Roeck, Swippert, & Verbakel, 2011). In other words: The higher the conductivity κ , the better a material conducts heat.

The definition of thermal conduction is:

$$q = -\kappa \nabla T$$

with:

q = Thermal conduction in W / m
 κ = Conductivity in W / m / K
 ∇T = Temperature gradient in K

Table 16

Thermal conductivity of various materials, solid between -40°C and +60°C

material	particulars	conductivity in W / m / K
Aluminium ¹	Depending on alloy	204 - 250
Brass ¹	Depending on alloy	109 - 125
Bronze ¹	Depending on alloy	26 - 50
Carbon nanotubes ²	Disordered	2,5 - 35
	Aligned mat	200
Copper ¹		385 - 400
Cork ⁴		0,04 - 0,07
Gold ¹		314 - 318
Extruded polystyrene ¹		0,03 - 0,39
Glass ¹		0,85
Graphene ³		5.000
Marble ¹		2,07 - 2,94
PMMA ¹	Plexiglas, Perspex	0,17 - 0,20
Polyethylene ¹		0,42 - 0,51
Rock Wool ⁴		0,04
Rubber ⁴		0,16
Silver ¹		400 - 430
Stainless steel ¹	Depending on alloy	16 - 24
Steel (mild) ¹	Depending on alloy	36 - 54
Titanium ¹		5 - 22,5
Wood ¹	Depending on species	0,04 - 0,40

¹ Polytechnisch Zakboek (2011); ² Carbon Nanotubes: Synthesis, Properties, and Applications (2009); ³ Royal Swedish Academy of Sciences (2010), ⁴ BINAS (1998).

Table 16 shows, that graphene would be best from a heat-conducting point of view. It is a one atom thick layer of Carbon, rediscovered in 2004 by Geim & Novoselov. It is not stiff, rigid or strong at all and therefore not suitable. All plastics have bad conductivity when without heat-conducting additives and of the metals, respectively silver, copper and gold would be best. Gold, silver and copper are very expensive and would be a waste of valuable material for this simple application. Stainless steel keeps very clean yet does not conduct heat that well. Next best thing is anodised aluminium. This is stiff, perfectly flat and corrosion resistive and will be non-growth-promoting.

10.5 The covering of the top layer

The aluminium of the top layer is a good thermal conductor. Still, the top of the device should be a thermal insulator to avoid conductive cooling of exposed skin of the lower arms of the human (Chapter 6) and paradoxically exchange heat radiation easily. This paradox can be solved with the right insulating layer, covering the visible side of the aluminium conductive wall. A layer of paint is a thermal insulator but can be very thin and is therefore apt as an isolator between the skin and the conductive aluminium.

10.6 The colour of the covering of the top layer

A perfect blackbody exchanges radiation with 100% efficiency. In practice, different objects of different materials are more or less efficient. This is indicated by the coefficient of emissivity ϵ . The higher the coefficient, the closer the material approaches the 100% efficiency of the perfect blackbody. In *thermal imaging*- creating an image based on the true heat radiation of an object or person- *emissivity* is a common factor.

The instruction manual of the Fluke Thermal Imager, used further ahead, explains *emissivity* clearly (comma's inserted instead of points in the numbers, etcetera):

Emissivity is defined as the ratio of the energy emitted at a temperature to the energy emitted by a perfect blackbody at that same temperature. A perfect blackbody would have an emissivity of 1,0. However, in the real world there is no such thing as a perfect blackbody. For example, if a perfect blackbody emits 10.000 W/m² at a given temperature and a material emits 5.000 W/m² at that same temperature, then the emissivity of that material is 0,5 or 50%. If another material emits 9.500 W/m² at that same temperature, it has an emissivity of 0,95.

It is important to note that for any opaque material, the ratio of energy reflected plus the ratio of energy transmitted is equal to 1,0 (this is known as Kirchhoff's Law). So if a material's emissivity is

0,95, the material reflects 5% of the energy radiated by objects facing it. By contrast, if an object has an emissivity of 0,50, the material reflects 50% of the energy radiated by objects facing it. This means this reflected energy can contribute to measurement accuracy. This is especially true when measuring materials with lower emissivity, and objects at lower temperatures (Fluke, 2007).

To have the insulating layer exchange heat easily, the emissivity should be as high as possible, indicated by a high coefficient of emissivity ϵ . Table 17 shows a selection.

Table 17
Coefficient of emissivity ϵ of various materials

material	particulars	ϵ , coefficient of emissivity
Black paint	Matte	0,97
White enamel	High gloss	0,90
Sheet metal	Steel	0,65
Glass	Absorbs certain frequencies	0,94
Rubber		0,90
Plastic		0,90
Cement		0,90
White paper	May contain optical whiteners	0,95
Aluminium	Anodised	0,30
Aluminium foil		0,10

Data from Fluke Corporation (2007).

According to Table 17, the best insulating layer would be matte black paint. Its emissivity is over 3 times as high as anodised aluminium and will hence improve the exchange of radiation.

The second approach is to establish the wavelength λ (or colour), the closest to the predominant wavelength a human radiates.

That can be done with the Wien law:

$$\lambda_{\max} = 0,0029 / T$$

This means, the temperature of an object can be determined from the wavelength of the heat radiation and the wavelength from the temperature (Middelink, 1992).

The human of Chapter 1 with a skin temperature of 33°C or 306K, will predominantly radiate a wavelength of:

$$\begin{aligned}\lambda_{\text{max, human}} &= 0,0029 / T \\ &= 0,0029 / 306\text{K} \\ &= 9,477 \times 10^{-6} \text{ m or } 947 \text{ nm}\end{aligned}$$

This is in the infrared spectrum, close to the visible light (see Figures 24 & 25).

Figure 24. The electromagnetic spectrum (Engineering ToolBox, 2016).

Figure 25. Visible light (NASA, 2010).

Black is the colour that (theoretically) absorbs all visible wavelengths and will probably be the best choice. To avoid impairments, caused by use, egg gloss paint may be a safer choice. Egg gloss may be less efficient than matte paint, yet the overall differences between paints are small: [*Matte AND Black*] relates to [*High Gloss AND White*] as 0,97 to 0,90. It can therefore be assumed, that any colour of paint or enamel is suitable and from matte to gloss.

10.7 Integration

The outcome of Paragraphs 10.1 to 10.6 can be added to the list of page 65 to form the program requirements for the final design.

The water distribution and top layer can be taken straight from the previous paragraphs: The proper performing CSM glass fibre mat, covered by an anodised sheet of aluminium, covered with a layer of egg gloss black enamel. The 6 small fans from the first designs can be reused again. Their sound output is low (*Very Faint*, see Paragraph 7.4) and, according to the program requirements, must be protected from contact and may be even more silent when shielded by, for example, the aluminium sheet.

The left-to-right airflow from Paragraph 10.3 seems an obvious yet adequate solution for the avoidance of draught, directed towards the user of the cooling device and the operating instructions, arising from the same paragraph- letting the device running overnight- will ensure, that the device dries out entirely.

It needs (preferably wider) air channels and a water reservoir- without any dead end tubing and stagnant water- below the aluminium top layer of the (preferably plane-parallel) device, made of non-growth promoting material, all with a clean, professional appearance.

Figure 26 shows the drawing of the top view of the final design of the chamber.

The vertical black dashed lines indicate the left and right edges of the CSM mat. The red dashed lines show the support for the CSM mat and the aluminium sheet upon it. The hatched parts support the aluminium directly. At the top and bottom are two full width gutters that form two water reservoirs. They are shallow to ensure they dry out easily and the full width ensures, that water gets in contact with the CSM mat over the full length without any tubing. The CSM is clamped between the top and bottom dashed lines and the hatched rectangles. The spaces between the rectangles let the water in. On the left are the 6 rectangular air intakes and on the right 6 exhausts. The air channels (between the horizontal red lines) are much wider. The left- and right-hand end of the bottom of the chamber hover 2 mm above the tabletop to form a concealed air intake and exhaust.

A complete set of drawings can be found in Appendix 1.

Figure 26. The main layout of the chamber of the cooling device.

A finished- milled- prototype of the chamber is shown in Figures 27 and 28. It is made from PVC-U. It is not as non-growth-promoting as PVC-C but will suffice because the chamber (and the other parts) will dry out entirely if the instructions for use are followed.

Figure 29 shows the inside of the assembled device: The CSM is clamped in place in the water reservoirs, the fans are wired in pairs in series and hooked up to a USB-cable. The water reservoirs are the full width grey areas that aren't covered by the CSM. There is no tubing whatsoever and no dead ends. The aluminium cover, painted egg-gloss-black, is on the chair on the left.

Figure 27. The milled prototype of the chamber of the final design.

Figure 28. The bottom of the final design with the fans on the left and the concealed inlet and exhaust on the left and right side.

Figure 29. The fully assembled chamber of the final design; On the chair the painted black aluminium cover.

The wall thickness of the bottom of the chamber is 2 mm, which makes the chamber quite flexible. To replenish the water reservoir, just flip up the right side of the device and lift up the aluminium through the exhaust.

With the cover on, the inside is shielded from daylight, preventing the growth of algae, the probable cause of the observed greenish deposits in the first real prototype of page 58 ff., and as mentioned on page 61.

The aluminium cover is held in place by a small ridge around it. The ridge is below the surface of the aluminium to avoid irritation to the skin and forms the decorative demarcation of the device.

(empty)

11: Pre-testing the final design

In Paragraph 1.6, it was determined, that:

- The face and ears have the highest density of thermoreceptors (Squire, 2009, Stevens & Choo, 1998) and
- The face perceives thermal changes in the environment the strongest (Yung-Bin, Jung, Park, Lee, 2017), and
- The facial skin area, under radiational heating, will cause 20% of the perspiration drive of the body (Nadel, Mitchell & Stolwijk, 1973).

Measuring the change in face temperature over time when exposed to the cooling device will hence be an indicator for the effectiveness of the device.

11.1 Method

11.1.1 Participants

The pre-test was conducted with two male participants, age 14 and 50.

11.1.2 Materials

The participants were exposed to a working or a non-working cooling device, placed on a tabletop in a spray painting booth of a car body repair shop. The two participants and their devices were separated by an insulating, vertical screen of two-wall polycarbonate. The booth was continuously ventilated with a constant airflow of 30°C / 50% RH to eliminate any influence of the working cooling device on the climate in the room.

11.1.3 Procedure

The participants entered the booth and set up the table for the test setting and were then seated for 30 minutes, not exposed to the cooling devices, to rest and get acclimatized to the conditions of the spray paint booth. Then, the participants were arbitrarily assigned to one of the coolers and switched places after 40 minutes. See Figure 30.

11.1.4 Measures

During the test, the temperature of the foreheads of the participants were monitored with a calibrated Fluke Ti25 *Thermal Imager* that measures actual temperatures on a 160 x 120 focal plane array. The coefficient of emissivity ϵ (see page 71 ff. in Paragraph 10.6) was kept at the camera's default value because the temperature *difference* was considered more important than its actual value. The measured values are shown in Table 18.

Over time, the temperatures of the exposed parts of the participants were also recorded with the thermal imager and displayed in *thermal images* in which identical colours represent identical temperatures.

Figure 30. The test set up in the spray paint booth.

Figure 30 shows the test setting. The brightly coloured rectangle in the middle is the thermal image in which the same colour indicates the same temperature, according to the legend at the bottom.

The sliding door on the left in the background has a window, cooler than the rest of the environment, indicated in blue. In the rear wall, above the two participants, is a light box with fluorescent tubes that is hotter than the rest of the environment, indicated in dark red. The distance of the window and fluorescent tubes to the participants is several metres and aim at the back of the participants and will therefore have had no influence on the front of the participants. On top of that, the 30°C / 50% RH air is refreshed actively.

The working cooling device is on the left in the pictures. Its surface is blue and thus on the cool side of the legend. The funnel-topped tubes in the left- and right-hand corners of the spray-painting booth distribute the airflow.

11.2 Results

The monitored forehead temperatures are shown in Table 18 alongside.

Table 18*Forehead temperature of the tested participants*

time	participant 1	participant 2
10:06h	cooled, 33,1°C	not cooled, 36,4°C
10:12h	cooled, 33,2°C	not cooled, 36,2°C
10:19h	cooled, 31,7°C	not cooled, 36,3°C
10:25h	cooled, 30,8°C	not cooled, 36,1°C
10:43h	cooled, 30,8°C	not cooled, 36,1°C
<i>switch</i>		
10:48h	not cooled, 34,0°C	cooled, 35,6°C
10:51h	not cooled, 35,3°C	cooled, 35,3°C
10:54h	not cooled, 35,8°C	cooled, 35,3°C
11:05h	not cooled, 35,3°C	cooled, 34,7°C
11:22h	not cooled, 35,8°C	cooled, 33,8°C

On the next pages the recordings of the temperatures of the exposed parts of the two participants in thermal images. Identical colours represent identical temperatures in all thermal images.

cold hot

Figure 31. Thermal image, 3 minutes after the start of the test, 10:06h.

cold hot

Figure 32. Just before switching, 10:43h.

cold hot

Figure 33. Just after switching, 10:48h.

cold hot

Figure 34. At the end of the test, 11:22h.

11.3 Discussion

At the working cooling device, the temperature *decrease* of the participants takes time, whereas the temperature *increase* of participant 1 after the switch is almost instantaneous.

At the non-working cooling device, the temperature of participant 2 stays stable. After the switch, the temperature decrease of participant 2 again takes time.

The pre-test indicates, that the cooling device effectively cools down the forehead skin of its user. According to Paragraph 1.6, this gives a pointer, people will indeed benefit from it.

Some electronic fever thermometers use the skin temperature of the forehead as reference. For the Braun NTF3000WF thermometer $> 35,7^{\circ}\text{C}$ - $37,4^{\circ}\text{C}$ are considered acceptable, $37,4^{\circ}\text{C}$ - $38,5^{\circ}\text{C}$ indicate an elevated temperature and $> 38,5^{\circ}\text{C}$ - $42,2^{\circ}\text{C}$ indicate possible high fever (Braun GmbH, 2014). In comparison with these bandwidths, the decrease of forehead temperature at the working cooler seems considerable.

The pretest testifies to the effectiveness of the cooling device.

To further study whether the cooler also contributes to a *perceived* decrease in temperature (i.e., the experience of a cooler, and a more comfortable environment), a follow-up testing in which these measures took centre stage was performed as set out in the next section. In this testing, the test set-up should be symmetrical and without any cool or hot spots, more or less aiming at only one of the participants- like the window and lightbox in the wall of the spray painting booth, see Figure 30- for the avoidance of any doubt regarding any influence of the test environment on the test results.

11.4 Recapitulation

The goal of the design of the new cooling device was, apart from being effective, to make it simple, silent, virtually windless, energy-efficient, environmentally friendly, inconspicuous, comfortable and healthy.

The cooling device meets all of the last items, the technical pre-test showed a measurable decrease of the participants' face temperature, it therefore influences the most sensible part of the human skin according to page 18 in Chapter 1.6, and, although a subjective observation, the participant at the working cooling device would stop sweating actively during the pre-test.

Still the effectiveness for its users is unknown:

People should also *perceive* the cooling effect.

12: Testing the perceived effect

The pre-test in the spray paint booth indicated, that the cooling device lowers the skin temperature of the forehead of its users, indicative for people cooling down. However, a measurable temperature decrease does not necessarily mean that people also experience the environment as cooler and more comfortable and pleasurable. They should *feel* cooled down.

Under supervision of Associate Professor dr. T.J.L. van Rompay, behavioural scientist at the Twente University in Enschede, The Netherlands, a blind test was conducted, solely focused on the *perception* of the cooling effect, without the use of the thermal imager.

12.1 Method

12.1.1 Participants

A total of 89 participants (30 males, 59 females; mean age 42,67 years) who arrived on foot or city-bike to enter a supermarket, were asked to participate in the experiment, making their initial condition more or less comparable.

12.1.2 Materials

The participants took place behind a laptop, placed on either a working or non-working cooling device. Both devices were powered up, only one was filled with water and hence effectively working. The laptops were used to fill in the surveys and the answers were collected in *Thesistools.com* via a mobile connection.

12.1.3 Procedure

To get constant circumstances, the test were conducted over two periods of the last 3 of 4 consecutive days with very constant, high summer weather: 30 - 31°C and 30 - 33% RH. The first day was omitted to make sure, the test subjects would indeed dress for high summer.

The test environment was a construction trailer, parked in front of a local supermarket, facing the south to get an even exposure to the sun and with written approval of the local City Counsel. The working and non-working cooling device were swapped every 10 double sessions.

People, intending to enter the supermarket, were asked to participate in a research project concerning the perception of interiors and, upon agreement, would then enter the trailer and were seated in a symmetrical setting at either the working or non-working cooling device. A short introduction would explain why the tests were conducted in a trailer (*We use a shanty to be able to perform this experiment at any given place and keep it scientifically sound.*) and the cover story: What would be expected from the participants (*You will first get a set of questions and then (to keep the participants longer inside) are asked to describe the view*) After this filler task people were asked to answer the first questions again. None of the participants asked about or seemed to notice the cooling devices before or during the surveys.

Figure 35. The test setting: A construction trailer in front of a supermarket.

Figure 36. The interior of and symmetrical test set up in the construction trailer. The wall-with-window faces the north.

12.1.4 Measures

The questionnaire started with questions about the participants' gender and age and then, between filler questions, were questions about their

- appreciation of the interior of the trailer in a 7-point rating from very oppressive (rated '1' in the statistics) to very agreeable (rated '7') and their
- estimation of the temperature in a pull-down menu, ranging from 15,0°C to 35,0°C. After the filler task- the participants' description of the view- the set of questions was repeated.

12.2 Results

The results have a *between-subjects* factor (*cooler on* or *cooler off*) and a *within-subjects* factor (the values for perceived comfort and for temperature estimation at *the start* and *the finish* of the test) and hence underwent a Mixed Model ANOVA (Mixed Model Analysis Of VAriance).

12.2.1 Appreciation of the interior of the trailer

The results for *Appreciation* supported the influence of the cooling device ($F(1, 86) = 13,218, p < 0,01$). Test subjects at the working cooling device appreciated the room better at the end of the test (mean: 0,86 rating points, SD: 1,30), contrary to the subjects at the non-working cooling devices who did not change opinion (mean: 0,00, SD: 0,85).

Three participants failed to answer both related questions about the appreciation of the interior.

See Figure 37.

Figure 37. Estimated marginal means of *positive* = increased appreciation.

12.2.2 Estimation of the temperature

Participants at the working cooling device estimated, the temperature in the trailer had dropped by the end of the test (corrected for °C: mean: -0,72°C, SD: 2,57), whereas the test subjects at the non-working cooling devices thought, the temperature had increased by the end of the test (corrected for °C: mean: +0,56°C, SD: 1,73), supporting the influence of the cooling device with ($F(1, 83) = 7,069, p < 0,01$) for a total difference of 1,28°C. Six participants failed to answer both related questions about the estimation of the temperature.

See Figure 38.

Figure 38. Estimated marginal means of the temperature.

12.2.3 Subjective observation

The subjective observation of the administrators of the tests, was, that the active sweating of subjects at the working cooling device would stop in course of the survey.

12.3 Discussion

None of the participants asked a question about the cooling devices. Only one participant inadvertently touched the underside of one of the cooling devices (these protruded from the table, see Figure 36) on her way out after she took the survey and wondered, what was swirling underneath.

Results of an ANOVA are considered significant, if $F > 4,0$ and $p < 0,050$ (Bortz & Schuster, 2010). This applies.

The results of the two main questions indicate, the cooling effect of the new cooling device is perceived.

Participants at the working cooling device indicated, that their appreciation of the room had increased over time whereas the participants at the non-working cooler did not change opinion.

The numerical estimation of the temperature also underlines the perceived effectiveness of the cooling device.

Considering the subjective observation of the administrators of the tests, that the participants at the working cooling device would stop sweating actively and the difference in estimated temperature by the participants at the working and the non-working cooling device for a total of $1,28^{\circ}\text{C}$, where the participants at the non-working cooling device would estimate, the temperature had, on average, risen $0,56^{\circ}\text{C}$ (which obviously did not happen, the temperature in the trailer was constantly monitored, did hardly fluctuate and did not exceed the outside temperature, which was also continuously monitored) and the participants at the working cooling device would estimate, the temperature, on average, had decreased ($-0,72^{\circ}\text{C}$), it can be concluded, that the effect of the cooling device *is* perceived, notwithstanding its subtle workings.

The questionnaire in full can be found in Appendix 2.

(empty)

13: Verification of the measurable effect

The pre-test in the spray paint booth in Chapter 11, showed, that the forehead temperature of the tested persons did indeed drop when exposed to the working cooling device. It did, however, take quite some time: 13 to 17 minutes. This in contrast to the heat-up, which only took 5 minutes after switching from working to non-working device.

The cool down time is very long for a verification test: It is difficult to persuade sufficient people to engage in a test that long. That was the reason to design a test that makes use of the quick heat-up:

Measure whether people, exposed to the working cooling device heat up slower than people exposed to a non-working device.

To achieve this, people were recruited at their arrival at a science and technology event in a Dutch middle-size city on two relatively cold and humid days (15°C with 66% RH and 16,5°C with 80% RH). The tests were again conducted in a construction trailer, now with a new, symmetrical layout, insulated and comfortably heated (25 - 27°C with 55 - 65% RH).

13.1 Method

13.1.1 Participants

A total of 40 participants (15 Female, 25 Male; mean age 35,63 years) were recruited on their arrival at the fair.

13.1.2 Materials

The materials, relevant for the test, were again two cooling devices, placed alongside each other as during the pre-test, both powered up, yet only one filled with water and thus working. Between the cooling devices and the participants was a two-wall acrylic sheet divider and the participants could enter through separate doors. Laptop computers- on which the participants would perform their surveys- were placed on top of the cooling devices. The answers of the actual survey were collected with ThesisTools.com on an external server via a mobile connection. The thermal images were again created with the Fluke Ti25 Thermal Imager from Chapter 11. The test set-up is shown in Figure 39. The divider is not installed in the picture.

13.1.3 Procedure

The tests were conducted in a construction trailer at the entrance of a science and technology event. The administrators of the survey, Master students of the Twente University, were instructed to select pedestrians and cyclists on arrival to participate in a scientific research project. To ensure that the test persons stayed in the trailer long enough to observe temperature fluctuations, they participated in an unrelated experiment on taste perception. Upon agreement, the test persons would then enter the trailer through their respective doors and were seated at either the working or non-working cooling device.

The administrators introduced the test and took individual, unrecognisable head shots with the thermal imager. When a participant indicated, she or he had finished the survey, again a head shot was recorded with the thermal imager.

Figure 39. The interior of the mobile laboratory in a construction trailer.

13.1.4 Measures

As indicated, the tests were conducted on relative cold days, where the participants would enter from the cold into a very well heated lab room. A thermal image of the test persons was taken at the start of every questionnaire, and again at the end of the session. The participants took 3 - 7,5 minutes to complete the survey with an average of 5' 10". The cooling devices were neither mentioned nor discovered or considered suspicious during all sessions. To assess the measurable cooling effect of the new cooling device, the thermal images, taken at the start of every questionnaire were compared to the images at the end of the questionnaire, to see, whether the difference in temperature of the facial skin at the start and ending would support the effect of the cooling device which, because of the difference between the outside (low) and inside (high) temperature, would mean:

A slower heat-up of the participant at the working cooling device.

The temperatures of the participants were measured using the software of the thermal imager. To get comparable averages, the measurements should be taken over an *as broad as possible* and *as narrow as necessary* selection of samplings from the pixels of the thermal image, representing the 160 x 120 thermometers (Fluke, 2007). The software allows single point measurements, circular and elliptical, square and rectangular, and linear selections. To get constant readings, the average was determined from an as long as possible linear selection over the exposed skin, following the centre of the nose of the participants. All thermal images, including the lines over which the averages were established, can be found in Appendix 3.

13.2 Results

The measurements again have a *between-subjects* factor (*cooler on or cooler off*) and a *within-subjects* factor (the measured temperatures at *the start* and *the finish* of the test), so the Mixed Model ANOVA was used again and supports the effect of the cooling device ($F(1, 40) = 4,1433, p < 0,05$): Participants at the working cooling device heat up more slowly (mean: 2,65°C, SD: 0,99) than participants at a non-working device (mean: 3,35°C, SD: 1,17).

Figure 40. Estimated marginal means of the measured temperature at the start and finish of the test.

On the next pages thermal images of two consecutive sessions, which show the slower heat-up of the persons at the working cooling device. Again, the same colours indicate the same temperatures.

Figure 41. Start of a session, on the left the working cooling device.

Figure 42. End of a session, on the left the working cooling device.

The participant on the left still shows *blue* (cold) in his face in Figure 42 whilst the lower part of the face of participant on the right has turned to *dark orange* with some *dark red* (hot). The clothes of the participant on the right have heated up more, too.

cold hot

Figure 43. Start of the next session, on the left the working cooling device.

cold hot

Figure 44. End of the next session, on the left the working cooling device.

Note the colour changes of the noses of the participants in particular.

13.3 Discussion

Most thermal images show a clear difference in the drop of temperature between the participants at the working and non-working cooling device, supporting the single result of the pre-test in the spray paint booth. Some of the values are very much not in line with the expectations (see Appendix 3), perhaps indicating, that some participants were cooled down very much, maybe after cycling fast or entering the lab from the rain or were

recruited *after* they had been inside or had arrived in a heated car.

Still, the outcome supports the influence of the cooling device.

Although the measured differences in drop of temperature are little in numerical terms (respectively 2,65°C and 3,35°C on average), the drop is large in terms of the bandwidths of the fever thermometer of Paragraph 11.3:
> 35,7°C - 37,4°C: acceptable, 37,4°C - 38,5°C: slight temperature, > 38,5°C - 42,2°C: possible high fever (Braun GmbH, 2014).

Again, nobody was suspicious about the cooling devices, asked about it or consciously discovered their subtle workings.

Now both the pre-test and the verification test supported the measurable influence of the cooling device, it is still unclear whether the effect is temporary or sustained over a long period of time. The pre-test showed a leveling-off after about a quarter of an hour. As of yet it is unknown whether the leveling-off indicates an inflection point or the sustained lower temperature level.

All thermal images of the verification test can be found in Appendix 3.

14: Is this new?

A *granted* patent gives the owner the right to exclude others from commercially making, using, offering for sale, selling or importing the invention, laid out in the patent, except for personal use. (World Intellectual Property Organization, United States Patent and Trademark Office, European Patent Office, Dutch Patent Law, etcetera). The usual maximum life span of a patent is 20 years.

When a patent is applied for, an examining procedure is gone through, to see, whether another inventor has applied for the same invention earlier on, or whether any other publication can be found, that discloses the same invention. The examiner, the person who draws up the resulting *search report*, is always an academic expert in the field of the patent.

In European patent law, a patent application is rejected if a *skilled person in the field of the invention* could create it from combining two existing patents. In US-American law it is officially three but sometimes- off the record- even four patents. If any other prior public available literature is found in which the invention is laid out, the patent application is rejected, too.

This required newness is called *novelty*. Apart from that, an invention must have *inventive step* (must be non-obvious), and must be *commercially applicable* to be granted a patent.

The system works both ways:

If an invention is considered to meet the three demands, the inventor can both exercise his patent rights and be (quite) sure, that she or he is not infringing on someone else's rights. The text of the claims of the patent are leading, they form the only real content of the granted patent right. The description and drawings are for clarification only.

Now for the new cooling device.

The idea of using the high enthalpy of vaporization of water to cool down things is not new at all. The human skin uses perspiration to keep cool, a water bag, as used in the desert, which skin lets some water seep through, will keep the water, left in the bag, relatively cool because of the heat extracted from the bag by the evaporation of the seeped-through water, just like a Roman Amphora, that was porous for the same reason.

To use the space between a roof of a car and the inside lining isn't new either: The earliest patent that came up in the examination procedure, using that space was filed on September 09, 1935: US21510907A, *Means and method for cooling vehicle bodies*, was invented by John A. Germonprez for the Evans Products Company, both from Detroit, Michigan, USA.

It is shown in Figure 45.

It suggests to make use of the driving speed of the vehicle to drive outside air through a chamber between roof and roof lining to maximize the effect of the

March 21, 1939.

J. A. GERMONPREZ

MEANS AND METHOD FOR COOLING VEHICLE BODIES

Filed Sept. 9, 1935

3 Sheets-Sheet 1

FIG. 1.

FIG. 1.

INVENTOR.
John H. Germonprez.
BY
Charles E. Henry
ATTORNEY.

2,151,097

In the European examining procedure, a Gebrauchsmuster- a German Utility Model- for cooling down a metro tunnel, invented by Horst Kickelhayn from Bergheim, Germany, was considered *closest prior art*. Years ago, this Gebrauchsmuster would never even have been considered in the examining procedure as it serves a different purpose in a different way. Now it was the definite hurdle to be taken because the claims contain the main features of the new cooling device (see Figure 46 alongside, a cross-section through the metro tunnel, for reference):

98 / 146

The design uses cold (cooled down), flowing water over the convex side of walls (2) to cool down the air within the concave side of walls (2)- the inner circle of the drawing- via convection. The now warmed up water is collected in gutters (8) that lead to a cooling machine. Condensation that forms on the 'dry' concave sides of the walls (2) also flows into these gutters.

Figure 46. Figure 4 of German Gebrauchsmuster DE 203 12 603 U1, *Anordnung zur Verbesserung der Raumatmosfera in einem Tunnelbau, insbesondere einer U-Bahnstation*, filed August 14, 2003, granted January 15, 2004.

The difference between this Gebrauchsmuster, the patent from Figure 45 and the new cooling device is, that the new cooling device intrinsically does not cause condensation as it only uses evaporation of water, spread over the heat-conducting wall, combined with the use of air from *within* the occupied space, hence never causing condensation on the face of the heat-conducting wall that

is facing the occupied space and only uses 'radiation absorption' (disturbance of the radiation balance) as a cooling mechanism.

In the procedures for the initial Dutch Patent Application, the following PCT-Application and the consequent EU-Application and US-Application, many other patents were cited. Some using pre-dried air, some using airflow on the 'dry' face of the heat-conducting wall, some using Peltier elements, and so forth, all focusing on maximizing the convectional cooling power within the system and all not intrinsically free from condensation. None of the systems focused on the disturbance of the radiation balance.

Both the EU and US-Patent for *Cooling Device* have been granted.

All documents on the procedures for the initial Dutch Patent Application, the PCT-Application and the EU-Application can be read on the site of European Patent Organisation EPO at:
<https://register.epo.org/application?number=EP10701571>

The US-Procedure is accessible via:
<https://portal.uspto.gov/pair/PublicPair>
and then entering 13/144573.
The documents are at the tab *Image File Wrapper*.

15: General discussion, Part 1

Until now, research has shown, that the new cooling device does measurably cool down (or heat up more slowly) its users (Chapter 11 and 13), and that users indeed perceive this cooling effect (Chapter 12). Still, it is unknown, whether the effect is temporary or sustained over a longer period.

Furthermore, the current design lacks any possibility of tuning the cooling power. This makes the device uncomplicated but the temperature drop was not properly assessed since the lab-model in Chapter 6. A test on a warm day (32,0°C, 50% RH, dew point 20,3°C), showed, that the device did approach the dew point with its fans spinning at full speed. It then reached a temperature drop of 10°C, twice the preferred maximum of 5°C. Temporary full speed spinning may be an improvement when sitting down at the device, although it does make the device noisy. The currently used fans are significantly louder than Akasa fan on page 48 in Paragraph 7.4. The same test initially showed, that the slightest obstruction of the air intake crevice would prevent the device from cooling down at all. See Figure 47. This problem did not occur during the tests of Chapters 11 and 13 because the tables were cleared. In the tests of Chapter 12, the fans and exhausts were even over the edge of the table. See Figure 36 on page 86.

Figure 47. Test of the cooling device on a hot day (32,0°C, 50% RH, dew point 20,3°C), the coefficient of emissivity ϵ at camera default. Top from left to right: The tabletop; The water supply bottle; The layer of CSM (wetted with water); The surface of the device at the start and After 9 minutes with the obstructed air intake. Bottom from left to right: Temperatures of the surface of the cooling device after 0, 3, 5, 8 and 10 minutes with the fans unobstructed and at full speed.

It still leaves one question unanswered:

Is the effect of the device is sustained over time?

This calls for a new, extended test of the new cooling device, with an air intake that cannot easily be obstructed and in a symmetrical test setting (without the asymmetrical colder window and warmer light box from the spray paint booth in Figure 30 on page 80) to make the measurements as certain as possible.

It should verify the pre-test of Chapter 11 and show, whether the lowest temperature in the pre-test was the inflection point or the sustained lower temperature level.

This extended test will conclude the research on the cooling device and is in Chapter 16 alongside.

16: Extended measurements

To verify the pre-test and find out, whether the lowest temperature in the pre-test was just the inflection point of the face temperature or the sustained lower temperature level, an extended version of the pre-test was performed.

16.1 Method

16.1.1 Participants

The test was conducted with two participants, one female, one male, both well trained (fat percentage resp. < 15 and < 10), both age 18, dressed in identical dry white T-shirts only, and kept at rest beforehand.

16.1.2 Materials

The participants were alternately exposed to a working or a non-working cooling device with an enlarged air intake and exhaust, placed on a tabletop in the symmetrical laid out mobile laboratory from Chapter 13.

The construction trailer was preheated to 30°C before the participants entered and was evenly exposed to the sun, with its window hatches closed.

Note: The floor, walls and windows of the laboratory are insulated but the roof is not. Not a problem on colder days as hot air rises.

16.1.3 Procedure

In the early morning of the second of two consecutive hot, high summer days (predicted maximum temperature above 30°C), the participants entered the construction trailer and were then seated for half an hour- not exposed to the cooling devices- to get acclimatised to the conditions of the trailer.

Then, the participants were arbitrarily assigned to one of the coolers and switched places after 45 minutes. After one and a half hours, the participants switched place for another half hour of exposure.

16.1.4 Measures

During the test, the temperatures of the exposed parts (upper body and face) of the participants were monitored, now with a FLIR One Thermal Imager that again measures actual temperatures on a 160 x 120 focal plane array (FLIR, 2016) and displays the results in thermal images (Figures 49 - 56). The operating temperature of the thermal imager is 0°C to 35°C (FLIR, 2015). The coefficient of emissivity ϵ in the software of the camera (again) was held at default.

The ambient temperature, relative humidity, background temperature, ceiling temperature and the temperature of the top surface of the non-working and working cooling device were also monitored.

16.2 Results

All measured values are shown in the graphs in Figure 48 on the next page.

Figure 48. Graphs of the measurements; Explanation alongside.

cold hot

Figure 49. Image at start;
On the right the working device.

Figure 50. Image before first switch;
On the right the working device.

Figure 51. Image after first switch;
On the right the working device.

Figure 52. Image, 30 minutes later;
On the right the working device.

The top graph displays the temperatures of the participants, followed by the measurements of the environment.

- **The temperature of the participants**, measured as per Chapter 13 (The verification of the measurable effect) started at 36,2°C (cyan) and 36,5°C (black). The lowest temperature registered was 33,6°C (working device), the highest 37,4°C (non-working device). The dashed line indicates 35,5°C.

- **The temperature of the working and non-working cooling device** show the working device consistently scoring > 5°C under the non-working device. The lowest temperature registered was 24,0°C (working device), the highest 37,5°C (non-working device) at the end of the test. The dashed line indicates 30,0°C.

- **The ceiling temperature** in magenta started at 21°C during heat-up and rose to 60°C at the end of the test. The dashed line indicates 40°C.

- **The background temperature** in green, measured on the rear wall between the heads of the participants, heated up very evenly, indicated by the even colours, started at 22°C to rise to 32°C. The dashed line indicates 27°C.

- **The relative humidity** in cyan shortly rose to a maximum of 68% to end at 51% at the end of the test. The dashed line indicates 55% RH.

- **The ambient temperature** in red rose from 20°C to 30°C during heat-up to end at 34°C, close to the maximum operating temperature of the thermal imager. The dashed line indicates 30°C.

Figure 53. After again 30 minutes;
On the right the working device.

Figure 54. Before second switch;
On the right the working device.

Figure 55. After second switch;
On the right the working device.

Figure 56. After again 30 minutes;
On the right the working device.

16.3 Discussion

The top graph in Figure 48 shows, that the effect is indeed sustained over time. In the pictures, it is clearly visible, that the influence of the cooling device on the faces *and* the exposed body parts of the participants is, and stays, considerable. The longer lines for establishing the average temperature, now over the faces and the dry-T-shirt-covered bodies, make, that the temperatures of the participants fluctuate less violently than in the pre-test, the influence on the face temperature still clearly indicated by the change in tone from deep orange at the start, via greenish patches at the lowest measured temperatures at the working cooling device (Figure 52 - 54 on the right) to the evident deep dark red upward parts (Figure 53 - 56).

Still, both participants do heat up near the end of the second, long test session, most likely caused by the vast, 40°C heat up of the ceiling. The ceiling caused the non-working device to get hotter than the ambient temperature:

The ceiling and the devices 'can see' each other very clearly and are plane-parallel and can thus exchange heat radiation easily (see Paragraph 1.4 on pages 15 - 16).

The upward sides of the arms, heads and shoulders of the participants heat up accordingly, indicated by the dark red patches in the later thermal images. The reduction in relative humidity, together with the increase in ambient temperature apparently caused the working cooling device to perform better and better as its topside stayed consistently below the initial ambient temperature of 30°C, notwithstanding it also being in direct and unobstructed heat radiation exchange with the ceiling. It was actually colder than the desired maximum of 5°C below the ambient temperature that is considered undetectable (ISO 7730:2005 & Van der Ree, 2009; See page 49) but the participants did not complain. They said, they perceived the cooling effect immediately after the switches.

The part of the background rear wall between the heads of the participants (that is where the background temperature was measured) heats up very evenly and symmetrically and clearly more quickly than the part below the shelf that is perpendicular to the rear wall (see Figure 39 on page 92). This will be caused by the heat of the ceiling, being 'reflected' from the shelf to the upper part of the wall and the shielding, 'shadow casting', effect of the shelf on the lower part. The shelf itself is in plain sight of the ceiling and hotter than the upper part of the wall, as indicated with the 'hotter' coloured horizontal bar.

In summary:

All is in line with the expectations of Chapter 1 (How humans lose their heat), Chapter 5 (The new cooling device) and Chapter 7 (The points of departure for the first real design) and the cooling effect is sustained over time.

17: General discussion, Part 2

In the introduction, I challenged myself to combine the most effective way to cool down a human with the most efficient cooling method and that the result- apart from being effective- should be simple, silent, virtually windless, energy-efficient, environmentally friendly, inconspicuous, comfortable and healthy.

This research, targeting the new cooling device from every angle I could imagine, to assess its usefulness, effectiveness, hygiene and simplicity is done: The new cooling device is indeed uncomplicated, environmentally friendly, energy-efficient and hygienic. People do indeed *perceive* the effect, and the influence on the temperature of the exposed parts of its users is indeed measurable and substantial. Its limitations are also known: High relative humidity will be detrimental for the efficacy of the device or even render it non-working and to avoid health issues, the use of clean water and drying out the device entirely, is essential. Still, the challenge is completed.

Yet..

Although the involved human physiology teaches, that people will indeed experience a lower *operative* temperature (see Figure 13 on page 39 and the definition on page 40 of Chapter 5), and the behavioural test showed, people do perceive an increase in comfort (see Chapter 12), it is still unknown whether there is an influence on the last aspect of thermal comfort, which, according to ISO 7730, is *the mental condition of the human* (see page 44 in Chapter 6).

This may- in my personal opinion- be the reason to add fan speed control: I think, hearing the fans blow for a short time is nice and gives the new cooling device credibility, albeit superfluous for its extended effect. If you don't hear it, the new cooling device is quite a mysterious thing. The buzzing fans may positively influence the mental condition of people.

I do tend to like to have an influence on my environment, like opening a window, which is supported by NEN 1087:2001 and ANSI/ASHRAE Standard 62.1-2016. Personalised ventilation, where individuals can control the amount of ventilation, makes, that the air quality close to the individual improves, and, beyond the measurable improvement, can better the thermal comfort by improving the thermal satisfaction of the individual, which implies an enhancement of his mental condition.

Products often cycle through different respective phases: Performance, Optimisation, Itemisation, Segmentation, Individualisation, and Awareness (Eger & Ehlhardt, 2018). The first phase is about functioning. That was the first test of Chapter 6: The tin bookshelf and the tea towel. Phase 2 starts with the final design: A product that is dependable and safe and ends with the pursuit of improved functionality, which in this case this could be the avoidance of possible obstruction of the air intake and exhaust, the addition of controls and a system to govern the drying out of the entire cooling device.

To that end and to complete this second phase, I have equipped one of the new cooling devices with larger air intakes and exhausts, added a two-speed fan control (*half speed* and *full speed* or *nearly inaudible* and *clearly whizzing*) with an *off-position* and a detachable USB-power cord.

LEDs at the right-hand top and bottom corners indicate respective empty water reservoirs, governed by humidity sensors, located in the outer sides of the water-spreading layer (which will be the last places to dry out).

Small holes in the aluminium top layer show the LEDs and allow water replenishment with a syringe without lifting the lid.

In the off-position or when the power cord is detached, a rechargeable battery will leave the fans turning until 30 minutes after the humidity sensors indicate, that the system is dry and the two water supplies depleted.

Because the difference in emissivity between matte black paint ($\epsilon = 0,97$) and glossy white paint ($\epsilon = 0,90$) is marginal compared to, for example, the influence of the relative humidity RH (see respectively Table 17 on page 72 and Table 5 on page 27), I had the top layer covered in a pretty satin white. In the end I *am* a designer.

Assessing the effect of the built-in controls may be the next step to investigate.

Still, I would venture to say, that the new cooling device actually works:

The final design cools down people and they do perceive it, too.

Thank you for your interest,

Matthijs Meulenbelt

18: Acknowledgements

When I was a bit under the weather, someone advised me, to diversify into matters where I could rely on a more methodic approach rather than on my individual intuition. This almost coincided with the plan to design a different motorcar, necessitating reliance on others.

The scientific approach also proved very appealing. My earliest friend Floris Tilanus told me- I paraphrase-: 'If the answer to the main question is 'No', it is *still* science.'

So when Arthur Eger suggested, it would be possible to write a dissertation on the design of a product, I gladly seized the opportunity. He and I often dwelled on many related and unrelated subjects during our meetings. *Education permanente*. He put up with me for years on end and introduced me to a- to me- new approach of assessing product design, which included behavioural science, and that's where Thomas van Rompay came into the picture. Thomas helped me in how to perform tests for perception and aided me often in the dos and don'ts in his métier and science in general. Arthur and Thomas have been critical yet kind teachers in more ways than as supervisors alone.

Being a classic β - merely technically focused- I had no knowledge of human physiology at all. After reading some introductory literature on it, Prof. Dr. Poul-Erik Paulev taught me years ago how the changes in the environment influence the thermoregulation of humans, quintessential to the entire approach to the new cooling device and resulting in the again quintessential Figure 13 on page 39. Professor Paulev died on June 25, 2017.

When I consulted Prof. dr. ir. Th. H. (Theo) van der Meer- he teaches thermodynamics- about my simple math on the device, Theo and I came to discuss all kinds of subjects. He encouraged me to add the influence on the 'it's in your head'-aspect of the cooling device, as addressed in the final general discussion, and actually commented most on Chapter 1 on human physiology. It was an interesting, lively and educating conversation, indeed.

Chapter 9, the health issues part, was reviewed by Prof. dr. ir. D. (Dick) van der Kooij, microbiologist. He is a leading expert on all matters regarding drinking water and has devoted many studies to biofilm forming and growth of *Legionella* in drinking water systems. His analytic mind set me to clarify Chapter 9 and clean up and make additions to Chapter 10. He also provided me with better, now scientific references for the ones I dug up in H₂O magazine, although both his' and mine covered some of the same studies.

The initial patent was written by Herman Schumann and Sandra van Kanten. Sandra, Herman and I have had an ocean of tea, discussing all kinds of matters. According to Sandra, Herman and I maintain a very altercating friendship ever since. He and I consider it engaged conversation.

To pay for the research, I have applied for a Valorisation Grant, which was granted by STW, Stichting voor de Technische Wetenschappen, part of NWO, Nederlandse Organisatie voor Wetenschappelijk Onderzoek (VG #10927) and lateron, together with Thomas van Rompay and Rob Tielbeke for a short-term energy research grant, granted by Agentschap NL, now part of Rijksdienst voor Ondernemend Nederland. Rob participated in co-financing the entire enterprise through Lux et Libertas B.V. and offered ongoing moral support and friendship.

The last two people I wish to honour are my daughter Eva and son Olivier, who I have often misused to help me out and have relentlessly battered with my constant chatter and questions about life, the universe and everything (Adams, 1979), including cooling devices.

Thank you all very much!

Matthijs

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(empty)

Appendix 1: A complete set of drawings

To avoid exposure to the airflow of the cooling device, the airflow is sideways. On both sides are 2 x 6 holes, on one side for the fans and on the other for the exhaust. The air intake and exhaust hover 2 mm above the tabletop, creating a crevice for the airflow. The two full width gutters at the top and bottom form the water reservoirs.

The black, dashed vertical lines demarcate the left and right edges of the CSM. The red, dashed horizontal lines show the support for the CSM, which clamps into the water reservoirs.

Figure 1-01. The main layout of the chamber of the cooling device.

The large surface and shallowness of the reservoirs will enable them to dry out thoroughly and the air channels are much wider now.

All, CSM, fans and water reservoirs, will be covered by a painted aluminium sheet metal cover, supported directly by the cross hatched sections and- with the CSM in between- by the ridges in red, dashed lines.

One ready milled part is shown in Figure 27 and Figure 28 in the main text. Figure 29, also in the main text, shows the device with its fans and the CSM installed, the fans wired in pairs in series and hooked up to a USB-cable.

Figure 1-02. The ridge that retains the aluminium sheet is crosshatched.

Figure 1-03. Crosshatched: support area for the alloy, milled down 0,5 mm.

Figure 1-04. Crosshatched: support under CSM, milled down 1 mm.

Figure 1-05. Crosshatched: bottom enforcement, milled down 6,0 mm.

Figure 1-06. The bottom level is crosshatched, milled down 8,0 mm.

Figure 1-07. Air intake and edge at bottom, milled down 2,0 mm.

Figure 1-08. The anodised aluminium cover, wall thickness 1,0 mm.

Figure 1-09. General dimensioning.

Figure 1-10. Radii.

Figure 1-11. The fan supports.

Appendix 2: The questionnaire in full

Start [button]

Ruimtebeleving testpersoon 1 (or 2)

Hartelijk welkom bij dit onderzoek naar algemene ruimtebeleving.

De enquête bestaat uit drie stukken:

- Een kort lijstje vragen dat begint met een paar vragen over uzelf;
- Het typen van een kort stukje en
- Een paar afsluitende vragen.

Het kost nog geen 10 minuten en u helpt ons erg op weg!

Aan het begin wordt u gevraagd tenminste aan te geven of u man of vrouw bent en hoe oud u bent. Als u op de hoogte gehouden wilt worden, vult u dan ook u uw email-adres in?

Als u iets niet begrijpt of iets onduidelijk vindt, dan kunt u het gewoon zeggen. Wél is het de bedoeling dat u uw antwoorden geheim houdt tijdens de enquête. Naderhand mag u er natuurlijk wél gewoon over praten.

Veel plezier!

Het onderzoeksteam

Start [button]

Ruimtebeleving testpersoon 1 (the same for person 2)

Eerst de vragen over uzelf.

- 1 Ik ben* [pull down] een vrouw / een man
- 2 Ik ben geboren in:* [pull down] geboortjaar
- 3 Ik wil op de hoogte gehouden worden van het onderzoek.
Mijn email-adres is: [invulvak]

Verder [button]

Dan nu de eerste vragenlijst.

- 4 Wat vindt u van de algemene verlichting van deze kamer?
De verlichting is: [7-keuze-bolletjes]
zeer onaangenaam zeer aangenaam

- 5 Wat vindt u van het kleurgebruik van deze kamer?
Het kleurgebruik is: [7-keuze-bolletjes]
zeer onaangenaam zeer aangenaam
- 6 Hoe vindt u de akoestiek van de kamer?
Het klinkt hier: [7-keuze-bolletjes]
zeer onaangenaam zeer aangenaam
- 7 Hoe bevalt uw stoel?
De stoel is: [7-keuze-bolletjes]
zeer oncomfortabel zeer comfortabel
- 8 Hoe vindt u de temperatuur in deze kamer?
De temperatuur is: [7-keuze-bolletjes]
zeer onaangenaam zeer aangenaam
- 9 Hoe hoog schat u de temperatuur? [pull down] °C
- 10 Wat is uw algemene indruk van deze kamer?
Deze kamer is: [7-keuze-bolletjes]
erg benauwend erg prettig

volgende pagina [button]

11

Uit onderzoek is gebleken, dat mensen veel belang aan het uitzicht hechten. Daarom vragen we u nu in circa 50 woorden te omschrijven wat u vindt van het uitzicht van deze kamer. Een regel of 5 tot 10 is ruim voldoende.

Heeft u hulp nodig, aarzel dan niet om te vragen.

Typ hier uw tekst. [invulvak]

volgende pagina [button]

Dan nu het afsluitende vragenlijstje.

We zijn heel benieuwd of u al een beetje gewend bent geraakt aan de omgeving.

- 12 Wat vindt u nu van de algemene verlichting van deze kamer?
De verlichting is: [7-keuze-bolletjes]
zeer onaangenaam zeer aangenaam
- 13 Wat vindt u nu van het kleurgebruik van deze kamer?
Het kleurgebruik is: [7-keuze-bolletjes]
zeer onaangenaam zeer aangenaam
- 14 Hoe vindt u akoestiek van de kamer nu?
Het klinkt hier: [7-keuze-bolletjes]
zeer onaangenaam zeer aangenaam

- 15 Hoe bevalt uw stoel inmiddels?
 De stoel is: [7-keuze-bolletjes]
 zeer oncomfortabel zeer comfortabel
- 16 Hoe vindt u de temperatuur in deze kamer?
 De temperatuur is: [7-keuze-bolletjes]
 zeer onaangenaam zeer aangenaam
- 17 Hoe hoog schat u de temperatuur nu? [pull down]
 °C
- 18 Wat is nu uw algemene indruk van deze kamer?
 Deze kamer is: [7-keuze-bolletjes]
 erg benauwend erg prettig

Enquête afronden [button = submit]

Dat was het al weer!

Heel hartelijk bedankt voor uw medewerking en als u uw email-adres heeft ingevuld, dan leest u nog van ons!

(empty)

Appendix 3: Verification of the measurable effect

To repeat the test on the measurable effect of the cooling device, to test the device under different circumstances and to make use of the quick heat-up, the verification tests were performed on colder days. The test was laid out to see whether the working cooling device would prevent people from warming up as quickly as the people at a non-working cooling device.

The thermal images were recorded at a science and technology event in a Dutch middle-size city on two relatively cold and humid days (15°C with 66% RH and 16,5°C with 80% RH), inside a comfortably heated and dry (25 - 27°C with 55 - 65% RH) *mobile laboratory*, a construction trailer with a new, entirely symmetrical and insulated interior, including the floor and the doors, equipped with double glazing, to avoid all possible influences of the environment on the measurements. See Figure 39 on page 92.

The administrators of the survey took individual, unrecognisable *head shots* with a *thermal imager* at the start and the end of the survey.

The temperatures of the participants were measured within the software of the thermal imager. To get comparable averages, the measurements were taken over an as *large as possible* and as *narrow as necessary* sampling (Fluke, 2007) from an as long as possible line over the exposed skin, following the centre of the nose of the participants.

The images on the next pages always show the persons at the *working* cooling device on the left and participants at the *non-working* device on the right and are in chronological order from top to bottom. Sessions with only one participant show only two images one above the other.

In other words: The *headshot*, taken at the start is above the one, taken at the ending of the unrelated survey.

Under every image are two lines of text:

The first gives the thermal image number, the participant number, 'device on' or 'device off' to indicate the working or non-working device, '@ start' or '@ end' to indicate whether it is the *head shot* at the start or at the ending of the survey, and on the second line gives the average temperature T , measured over the line in the picture and, where applicable, ΔT , which indicates the temperature increase, calculated from T at the end minus T at the start of the survey [$\Delta T = T @ \text{end} - T @ \text{start}$].

The same colours indicate the same temperature according to this legend:
cold, 24°C 36°C, hot

In this column working devices.

409: Person 01, device on @ start;
 $T = 33,7^{\circ}\text{C}$.

411: Person 01, device on @ end;
 $T = 34,8^{\circ}\text{C}$, $\Delta T = 1,1^{\circ}\text{C}$.

In this column non-working devices.

410: Person 02, device off @ start;
 $T = 33,6^{\circ}\text{C}$.

412: Person 02, device off @ end;
 $T = 35,9^{\circ}\text{C}$, $\Delta T = 2,3^{\circ}\text{C}$.

In the right column is a single session at the non-working cooling device.

413: Person 03, device off @ start;
 $T = 32,8^{\circ}\text{C}$.

414: Person 03, device off @ end;
 $T = 35,6^{\circ}\text{C}$, $\Delta T = 2,8^{\circ}\text{C}$.

In this column working devices.

415: Person 04, device on @ start;
 $T = 32,9^{\circ}\text{C}$.

418: Person 04, device on @ end;
 $T = 35,2^{\circ}\text{C}$, $\Delta T = 2,3^{\circ}\text{C}$.

419: Person 06, device on @ start;
 $T = 28,7^{\circ}\text{C}$.

420: Person 06, device on @ end;
 $T = 31,3^{\circ}\text{C}$, $\Delta T = 2,6^{\circ}\text{C}$.

In this column non-working devices.

416: Person 05, device off @ start;
 $T = 31,8^{\circ}\text{C}$.

417: Person 05, device off @ end;
 $T = 34,1^{\circ}\text{C}$, $\Delta T = 2,3^{\circ}\text{C}$.

*In the left column a single session
at the working cooling device.*

In this column working devices.

421: Person 07, device on @ start;
 $T = 29,9^{\circ}\text{C}.$

423: Person 07, device on @ end;
 $T = 32,0^{\circ}\text{C}, \Delta T = 2,1^{\circ}\text{C}.$

425: Person 09, device on @ start;
 $T = 28,9^{\circ}\text{C}.$

428: Person 09, device on @ end;
 $T = 33,4^{\circ}\text{C}, \Delta T = 4,5^{\circ}\text{C}.$

In this column non-working devices.

422: Person 08, device off @ start;
 $T = 31,0^{\circ}\text{C}.$

424: Person 08, device off @ end;
 $T = 35,6^{\circ}\text{C}, \Delta T = 4,6^{\circ}\text{C}.$

426: Person 10, device on @ start;
 $T = 29,0^{\circ}\text{C}.$

427: Person 10, device on @ end;
 $T = 32,7^{\circ}\text{C}, \Delta T = 3,7^{\circ}\text{C}.$

In this column working devices.

429: Person 11, device on @ start;
 $T = 26,7^{\circ}\text{C}$.

432: Person 11, device on @ end;
 $T = 30,5^{\circ}\text{C}$, $\Delta T = 3,8^{\circ}\text{C}$.

433: Person 13, device on @ start;
 $T = 30,3^{\circ}\text{C}$.

436: Person 13, device on @ end;
 $T = 32,4^{\circ}\text{C}$, $\Delta T = 2,1^{\circ}\text{C}$.

In this column non-working devices.

430: Person 12, device off @ start;
 $T = 29,5^{\circ}\text{C}$.

431: Person 12, device off @ end;
 $T = 31,4^{\circ}\text{C}$, $\Delta T = 1,9^{\circ}\text{C}$.

434: Person 14, device off @ start;
 $T = 30,4^{\circ}\text{C}$.

435: Person 14, device off @ end;
 $T = 32,7^{\circ}\text{C}$, $\Delta T = 2,3^{\circ}\text{C}$.

In this column working devices.

437: Person 15, device on @ start;
 $T = 29,6^{\circ}\text{C}.$

439: Person 15, device on @ end;
 $T = 31,9^{\circ}\text{C}, \Delta T = 2,3^{\circ}\text{C}.$

441: Person 17, device on @ start;
 $T = 28,1^{\circ}\text{C}.$

443: Person 17, device on @ end;
 $T = 30,4^{\circ}\text{C}, \Delta T = 2,3^{\circ}\text{C}.$

In this column non-working devices.

435: Person 16, device off @ start;
 $T = 29,4^{\circ}\text{C}.$

440: Person 16, device off @ end;
 $T = 34,1^{\circ}\text{C}, \Delta T = 4,7^{\circ}\text{C}.$

442: Person 18, device off @ start;
 $T = 29,7^{\circ}\text{C}.$

444: Person 18, device off @ end;
 $T = 33,3^{\circ}\text{C}, \Delta T = 3,6^{\circ}\text{C}.$

In this column working devices.

445: Person 19, device on @ start;
 $T = 30,7^{\circ}\text{C}$.

446: Person 19, device on @ end;
 $T = 32,5^{\circ}\text{C}$, $\Delta T = 1,8^{\circ}\text{C}$.

And on the right one at the non-working device.

In this column non-working devices.

In the left column again a single session at the working cooling device.

447: Person 20, device off @ start;
 $T = 31,3^{\circ}\text{C}$.

448: Person 20, device off @ end;
 $T = 35,6^{\circ}\text{C}$, $\Delta T = 4,3^{\circ}\text{C}$.

In this column working devices.

449: Person 21, device on @ start;
 $T = 31,2^{\circ}\text{C}$.

451: Person 21, device on @ end;
 $T = 34,0^{\circ}\text{C}$, $\Delta T = 2,8^{\circ}\text{C}$.

453: Person 23, device on @ start;
 $T = 33,2^{\circ}\text{C}$.

454: Person 23, device on @ end;
 $T = 34,8^{\circ}\text{C}$, $\Delta T = 1,6^{\circ}\text{C}$.

In this column non-working devices.

450: Person 22, device off @ start;
 $T = 29,4^{\circ}\text{C}$.

452: Person 22, device off @ end;
 $T = 33,3^{\circ}\text{C}$, $\Delta T = 3,9^{\circ}\text{C}$.

*On the left again a single session
at the working cooling device.*

In this column working devices.

455: Person 24, device on @ start;
 $T = 26,6^{\circ}\text{C}$.

458: Person 24, device on @ end;
 $T = 29,1^{\circ}\text{C}$, $\Delta T = 2,5^{\circ}\text{C}$.

459: Person 26, device on @ start;
 $T = 27,6^{\circ}\text{C}$.

461: Person 26, device on @ end;
 $T = 30,1^{\circ}\text{C}$, $\Delta T = 2,5^{\circ}\text{C}$.

In this column non-working devices.

456: Person 25, device off @ start;
 $T = 28,4^{\circ}\text{C}$.

457: Person 25, device off @ end;
 $T = 31,6^{\circ}\text{C}$, $\Delta T = 3,2^{\circ}\text{C}$.

460: Person 27, device off @ start;
 $T = 30,5^{\circ}\text{C}$.

462: Person 27, device off @ end;
 $T = 32,9^{\circ}\text{C}$, $\Delta T = 2,4^{\circ}\text{C}$.

In this column working devices.

463: Person 28, device on @ start;
 $T = 29,4^{\circ}\text{C}.$

465: Person 28, device on @ end;
 $T = 32,7^{\circ}\text{C}, \Delta T = 3,3^{\circ}\text{C}.$

467: Person 30, device on @ start;
 $T = 32,5^{\circ}\text{C}.$

469: Person 30, device on @ end;
 $T = 34,1^{\circ}\text{C}, \Delta T = 1,6^{\circ}\text{C}.$

In this column non-working devices.

464: Person 29, device off @ start;
 $T = 28,1^{\circ}\text{C}.$

466: Person 29, device off @ end;
 $T = 32,9^{\circ}\text{C}, \Delta T = 4,8^{\circ}\text{C}.$

468: Person 31, device off @ start;
 $T = 30,1^{\circ}\text{C}.$

470: Person 31, device off @ end;
 $T = 33,6^{\circ}\text{C}, \Delta T = 3,5^{\circ}\text{C}.$

In this column working devices.

*On the right again a single session
at the non-working device.*

In this column non-working devices.

471: Person 32, device off @ start;
 $T = 28,9^{\circ}\text{C}$.

472: Person 32, device off @ end;
 $T = 32,2^{\circ}\text{C}$, $\Delta T = 3,3^{\circ}\text{C}$.

474: Person 33, device on @ start;
 $T = 28,7^{\circ}\text{C}$.

476: Person 33, device on @ end;
 $T = 32,9^{\circ}\text{C}$, $\Delta T = 4,2^{\circ}\text{C}$.

475: Person 34, device off @ start;
 $T = 28,0^{\circ}\text{C}$.

477: Person 34, device off @ end;
 $T = 34,4^{\circ}\text{C}$, $\Delta T = 6,4^{\circ}\text{C}$.

In this column working devices.

479: Person 35, device on @ start;
 $T = 30,4^{\circ}\text{C}.$

481: Person 35, device on @ end;
 $T = 34,3^{\circ}\text{C}, \Delta T = 3,9^{\circ}\text{C}.$

482: Person 37, device on @ start;
 $T = 34,1^{\circ}\text{C}.$

484: Person 37, device on @ end;
 $T = 35,7^{\circ}\text{C}, \Delta T = 1,6^{\circ}\text{C}.$

In this column non-working devices.

478: Person 36, device off @ start;
 $T = 31,9^{\circ}\text{C}.$

480: Person 36, device off @ end;
 $T = 34,4^{\circ}\text{C}, \Delta T = 2,5^{\circ}\text{C}.$

483: Person 38, device off @ start;
 $T = 34,5^{\circ}\text{C}.$

485: Person 38, device off @ end;
 $T = 36,4^{\circ}\text{C}, \Delta T = 1,9^{\circ}\text{C}.$

In this column working devices.

486: Person 39, device on @ start;
 $T = 29,8^{\circ}\text{C}$.

488: Person 39, device on @ end;
 $T = 33,9^{\circ}\text{C}$, $\Delta T = 4,1^{\circ}\text{C}$.

In this column non-working devices.

487: Person 40, device off @ start;
 $T = 32,8^{\circ}\text{C}$.

489: Person 40, device off @ end;
 $T = 35,4^{\circ}\text{C}$, $\Delta T = 2,6^{\circ}\text{C}$.

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Colophon

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Main text: Optima

This is also little nod to my father,
ir. Henri Sophinus Meulenbelt, b.i.
Architect, *1934 - †1994

Appendices: Arial

Meulenbelt (1965, Almelo, The Netherlands), was brought up, surrounded by architecture, art, design, private roads, farmers, manure and all sorts of vehicles.

From his early days, he made 'improvements' to his and others' possessions. A dear learning process of trial and many, many errors.

At the age of 8, he discovered the lasting pleasures of motorised vehicles for personal use.

From grammar school onward, he took an ever more serious interest in physics, engineering, art and design, resulting in the obvious but deliberate choice for a study in Industrial Design Engineering at the Delft University of Technology, and earned his Master's on the design of a motorcycle, supervised by three professors.

Next to his studies, he realised his first real-world and award-winning design, the undercarriage of a land yacht, and he evolved into an independent industrial designer, catering to a broad spectrum.

After a few years of almost honorary one-afternoon-a-week-part-time teaching at the AKI, now Artez University of the Arts in Enschede, he joined the board of the Dutch Designers Association (bNO) as a honorary member and presided its industrial design department.

The entire process of manufacturing and the innovation thereof, from the mechanics and mould production to ergonomics and the clean and professional appearance sought after, has his interest and led him to become more and more of an inventor, once in a while interrupted by design projects for smaller scale series production, commissioned art and one-off furniture.

His major feat of arms is a LED-module for the internal illumination of light boxes, clearly improving the light distribution and energy efficiency, and now a leading product in worldwide signage.

The start of a car company brought him in contact with Prof. dr. ir. Arthur O. Eger and the University of Twente, where he supervised several Bachelor and Master students, taught a few Master's courses, eventually culminating in this dissertation.

Meulenbelt is a single parent of two and lives in Borne, The Netherlands.